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# ENVIRONMENTAL CONDITIONS IN COASTAL WATERS NEAR PANAMA CITY, FLORIDA



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ADMINISTRATIVE INFORMATION (U)

The information appearing in this report is a byproduct of practically every water-related task in which NCSC has been engaged during the past two decades. Far too numerous to mention by name, these tasks provided most of the funds for making the environmental measurements upon which our present understanding is based. Need for a concise description of the local coastal environment prompted the authors to compile the results of these measurements into a single volume. The bulk of the writing was funded by the Advanced Submarine Control Program (Program Element 63561N project S0207, Work Unit 20812).

The authors wish to acknowledge the assistance of all their colleagues in the Environmental Sciences Division, who offered many fine suggestions, supplied much valuable information, and made most of the measurements and original observations.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report is a concise description of coastal environmental conditions in the vicinity of Panama City, Florida. It contains information regarding the bathymetry and bottom characteristics of the nearby Gulf of Mexico and St. Andrew Bay, as well as descriptions of local weather phenomena, wave action, tides, currents, water temperature, salinity, density, sound velocity, clarity, and selected marine biological activity. Seasonal variations are emphasized.

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# INTRODUCTION

During the past two decades, the Naval Coastal Systems Center (NCSC) at Panama City, Florida, has conducted a wide variety of military tests and evaluations in the waters of the Gulf of Mexico and St. Andrew Bay (Figure 1). Laboratory oceanographers have collected a large quantity of environmental data during these tests, and have gained considerable knowledge of the characteristics of the local coastal area, and the distribution and variability of associated parameters. Unfortunately, much of this information and knowledge is not readily accessible to the personnel charged with the responsibility of planning future field tests. It lies hidden in the minds of local environmentalists, and in the appendices of countless individual test reports, many of which have never received wide distribution and have been largely forgotten over the years. It is the purpose of this report to compile these various pieces of information into a concise one volume description of the local coastal area to which laboratory scientists, engineers, and the military can refer for effective planning purposes.

Many publications were examined during the course of this compilation, and those from which information was extracted are duly referenced. Particularly noteworthy are the works of Tolbert and Austin (Reference 1), Ichiye and Jones (Reference 2), Pidgeon and Pidgeon (Reference 3), and Dowling (Reference 4). However, much of the information in this report has never before been published. It was supplied by various members of the NCSC oceanographic staff, many of whom have been studying and diving in local waters for more than 20 years - both in a professional capacity and as a hobby. These inquisitive men have experienced the flood and ebb of many tides, have witnessed the nearby gulf in all its moods, and explored a significant portion (practically every nook and cranny) of the local seafloor. Their direct observations have spanned many seasons and comprise a storehouse of valuable information which far outweighs the body of knowledge obtained by conventional ship-bound investigators. The bulk of the credit for this document belongs to these dedicated diving oceanographers.

This report consists of seven major sections, the first of which provides background information regarding the general configuration and bathymetry of the nearby bay, inlets, beaches, and shelf waters, and the location of prominent local facilities. The second section contains a description of the various types of weather which can be expected during

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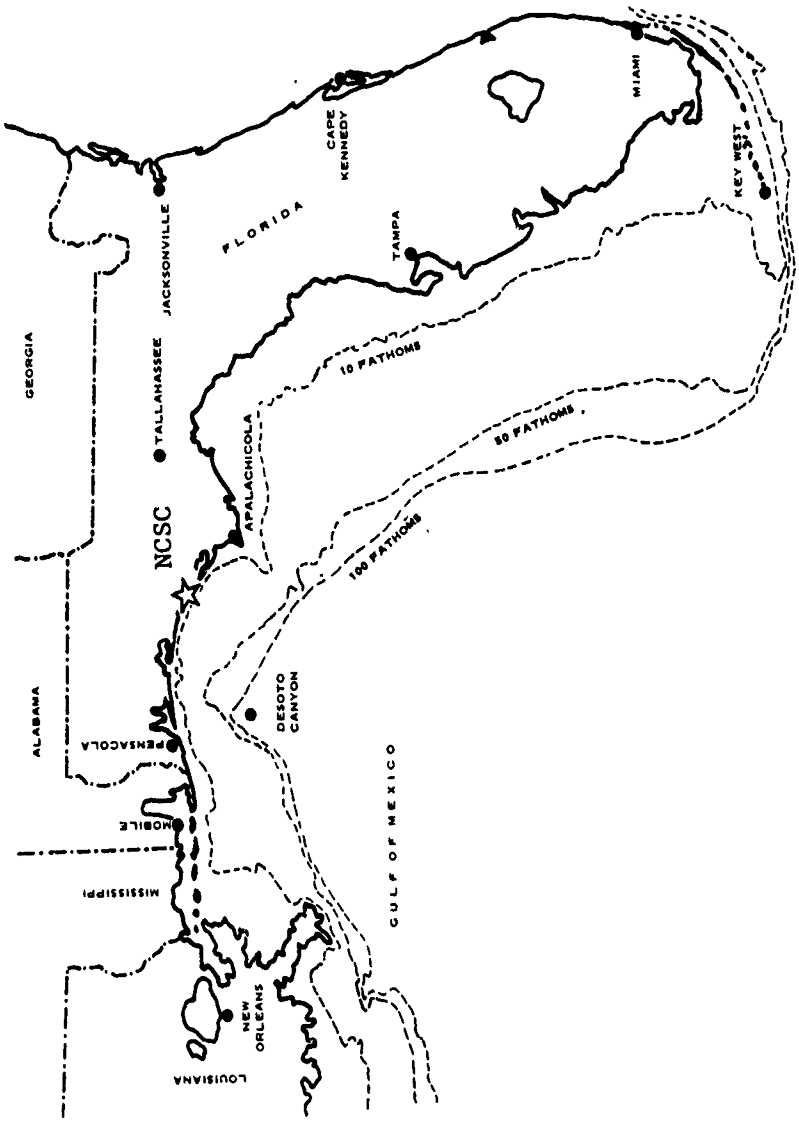


FIGURE 1. LOCATION MAP

each season. Subsequent sections contain descriptions of local surface wave conditions and tidal fluctuations, surface and subsurface current flow, water column characteristics (temperature, salinity, density, sound velocity, and turbidity), bottom conditions, and selected biological characteristics.

## GENERAL AREA DESCRIPTION

### PHYSICAL LAYOUT

Panama City and NCSC are located on the shores of the St. Andrew Bay system, a modest stream-fed estuary which empties into the Gulf of Mexico approximately 230 nautical miles (420 km) east of New Orleans. The configuration of the bay system's three major arms is depicted in Figure 2. These arms are named East Bay, North Bay, and West Bay. The shores of each arm are indented by numerous small bayous. Total surface area of the entire bay system is approximately 90 square miles (233 km$^2$). As shown in Figure 2, the city of Panama City is located near the mouth of the bay's east arm, and NCSC is located approximately 5 miles (8 km) west of the city.

According to geologists the bay was formed during the Holocene Transgression (3000 to 20,000 years ago) when seas rose to their present level and flooded the tributary valleys of the local stream system. Greatest depths are thus generally found within meander-like channels located along the central axis of each arm of the bay. The central portion of bay varies from 35 to 50 feet (10.6 to 15.2 m) deep in the vicinity of NCSC. Maximum water depth within the bay is approximately 65 feet (19.8 m).

The bay system connects with the Gulf of Mexico through two entrance channels, one natural and the other man-made. The latter entrance is situated 4 miles southwest of Panama City. Cut through a coastal dune formation by the Corps of Engineers in 1934, this channel handles practically all present-day ship traffic between bay and gulf. Periodic dredging is required to allow ocean-going vessels to pass over a bar at its mouth. Depths along this 500-ft (152 m) wide channel range from 30 to 55 feet (9 to 17 m). Rock jetties line its seaward edges. The natural entrance to the bay is located 5 miles (8 km) southeast of the man-made ship channel. Depths across the shallow bar guarding this natural entrance are generally less than 8 feet. The offshore dune landmass between entrances is known as Shell Island.

Shores of the nearby Gulf of Mexico are lined with beautiful white sand beaches which extend over 100 miles (160 km) eastward and westward

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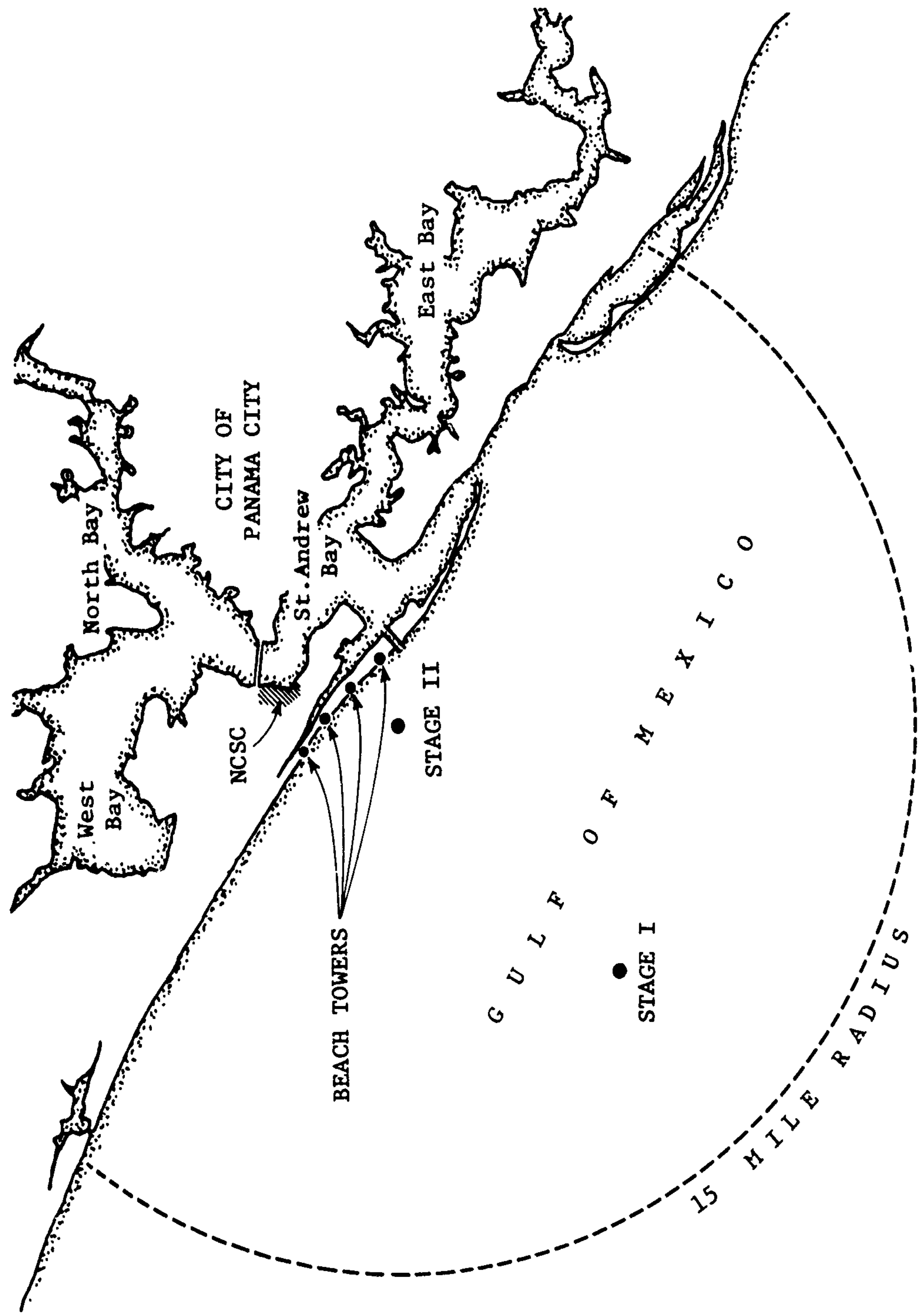


FIGURE 2. GULF OF MEXICO AND BAY AREAS

of Panama City. As shown in Figure 1, the most prominent features of the northeastern Gulf shoreline are (1) the ancient delta of the Apalachicola River, which protrudes out into the Gulf about 50 miles (80 km) southeast of Panama City, and (2) the modern delta of the Mississippi River which continues to grow out onto the shelf 200 miles to the west of Panama City. A gently curving coastline between these two deltas is backed by low-lying dune systems and typical coastal plain pine forests. Shallow sand bars lie just offshore. Seaward of the bars, the bottom dips to a depth of 50 feet (15 m) within 1 mile (1.6 km) of the beach, then slopes more gradually. The 60-foot (18 m) depth contour is located about 1.5 miles (2.4 km) offshore, while the 100 and 500-foot (30 and 150 m) depth contours are located 11 and 30 miles (18 and 48 km) southwest of the entrance to St. Andrew Bay. The region contains only one significant geological feature - submerged de Soto Canyon - the head of which cuts into the shelf about 70 miles (113 km) westsouthwest of Panama City.

A typical depth profile across the local shelf is shown in Figure 3 which was taken from Reference 5. The shelf break occurs about 35 nautical miles (51.5 km) offshore in approximately 165 feet (50 m) of water. The bottom deepens more rapidly seaward of this break, eventually reaching a depth of 1300 feet (396 m) 75 nautical miles offshore on the eastern flanks of de Soto Canyon. Depths increase rapidly further to the southwest where the canyon widens. Depths of more than 2 miles (3200 m) have been logged in the central portion of the Gulf of Mexico.

## LOCAL FACILITIES

NCSC maintains various local facilities to help engineers and scientists conduct their field tests. Among these facilities are two offshore research platforms, a series of beach towers for optical tracking purposes, a heliport, dock space for ships, a radar surveillance system, diving locker, ocean simulation facility, and an environmental measurement system. Positions of the two offshore platforms and four beach tracking towers are shown in Figure 2. Stage I is located approximately 12 miles (19 km) offshore in 105 feet (32 m) of water. Stage II, closer to shore, is located approximately 1.5 miles (2.4 km) offshore in 60 feet (18 m) of water. Beach tracking towers are situated on prominent gulfside dunes, and are located approximately 1, 2, 3, and 4 nautical miles northwest of the St. Andrew Bay entrance channel. Most other facilities are located on the Center's bayfront property. Tyndall Air Force Base is located on the low peninsula of land separating East Bay from the Gulf of Mexico.

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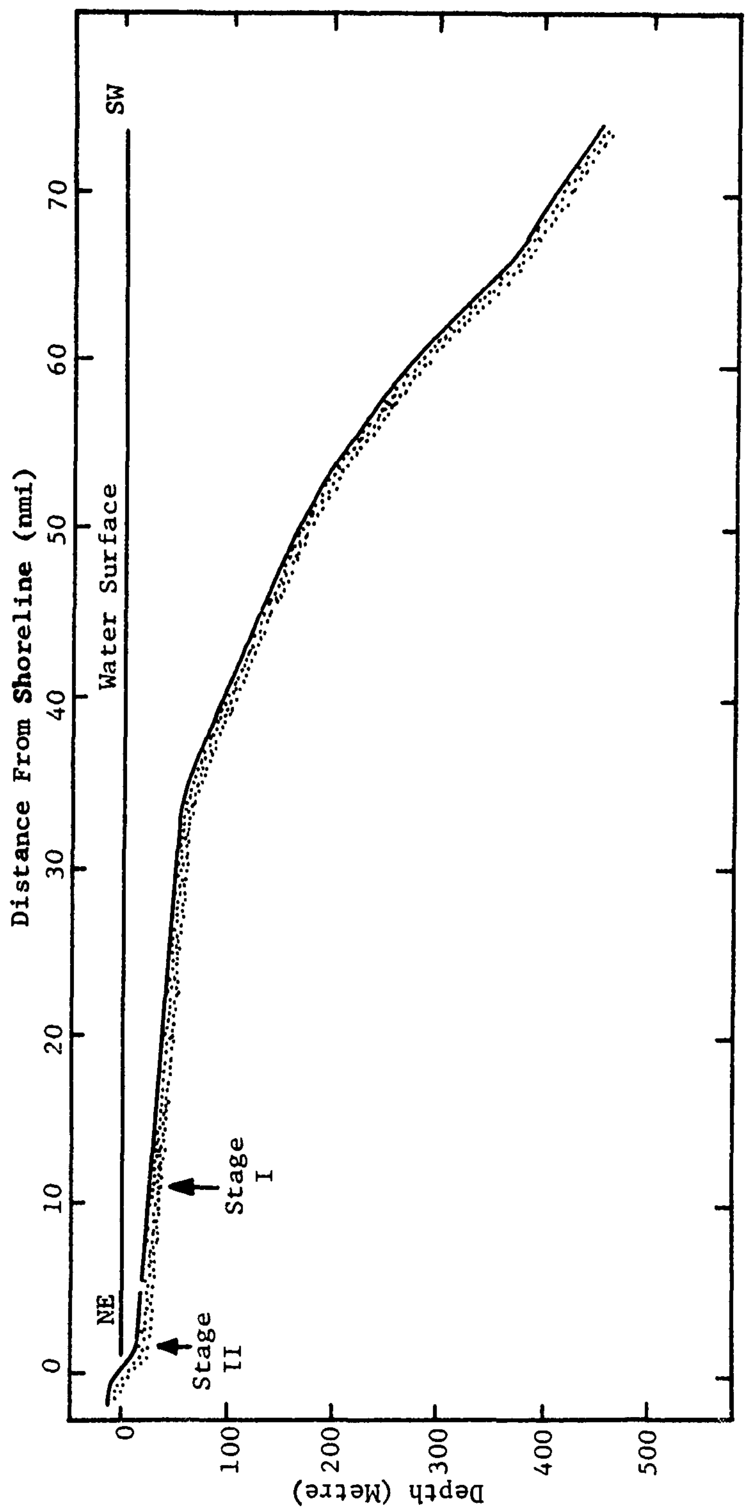


FIGURE 3. GULF BOTTOM PROFILE IN SHELF AREA

# WEATHER CONDITIONS

## GENERAL

The northwestern Florida coastal area enjoys a warm, humid, semi-tropical climate for most of the year, with occasional intervals of cooler but stormier weather during winter months (Reference 6). This area lies within a climatic belt known as the horse latitudes, a band of relatively high pressure separating the trade wind belt (to the south) from the zone of prevailing westerly winds (to the north). Resulting weather patterns are thus bimodal, exhibiting tropical characteristics during some periods (especially summer), and vacillating between temperate and tropic conditions during other seasons.

### Storms

Three general types of stormy weather are encountered: (1) cold fronts, which are associated with extra-tropical low pressure systems moving in from more northerly latitudes, (2) hurricanes, or tropical disturbances, which form at low latitudes and migrate into the Gulf of Mexico from the Atlantic Ocean or the Caribbean Sea, and (3) thunderstorms, which usually form in local skies on hot humid days. Typical annual variations in the frequency of occurrence of these three general weather types are shown in Figure 4 (from Reference 7). The upper curve shows that cold fronts pass through the Panama City area most frequently during winter, occasionally during spring and fall, and practically never during summer. A curve depicting the local frequency of occurrence of thunderstorms is of opposite phase, reaching its peak during summer rather than winter months. The relatively few thunderstorms which occur during winter are almost always associated with cold front passages rather than local heating. The middle curve in Figure 4 shows that the frequency of occurrence of tropical storms (hurricanes) in the western North Atlantic Ocean, Caribbean Sea, and Gulf of Mexico is greatest during the months of August, September, and October. The official hurricane season extends from May to November.

### Winter

Typical winter weather pattern is dominated by extra-tropical frontal systems, which periodically sweep down from the central plains. Prior to the arrival of each front, weather is generally warm and humid, and winds blow from a southerly to southeasterly direction, gradually increasing in speed and causing local seas to build. Frontal passage(s) are usually accompanied by strong winds, heavy seas, and rainshowers. The wind shifts abruptly to a northwesterly or northerly direction after a frontal passage. Rain then stops, skies clear, air temperature and humidity decrease rapidly, and seas gradually begin to subside. The

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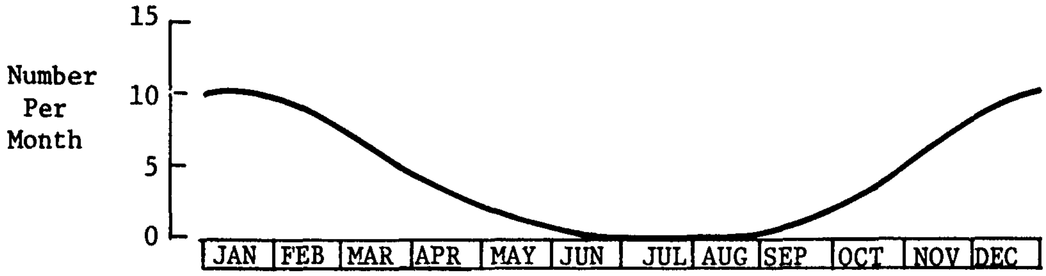
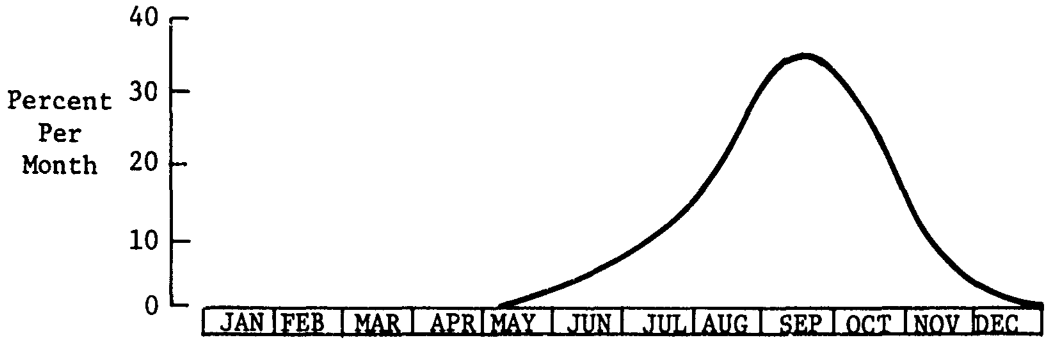
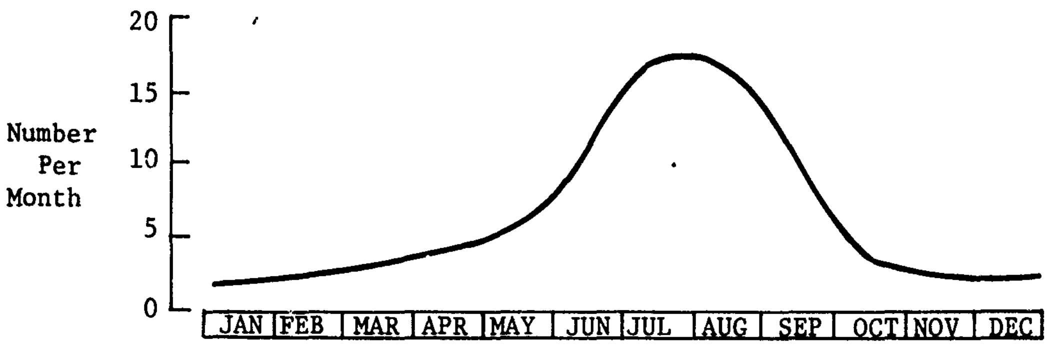



Frequency of Frontal Passages at Panama City, Florida




Frequency of Tropical Storms in the Western North Atlantic, Caribbean and Gulf of Mexico




Frequency of Thunderstorm Days at Panama City, Florida

FIGURE 4. TYPICAL ANNUAL STORMY WEATHER VARIATIONS

area then enjoys several days of clear, cool weather, light winds, and minimal wave action as a ridge of high pressure migrates eastward toward the Atlantic Ocean. Temperature and humidity gradually increase during the latter part of this period as winds swing around from north through east to southerly directions, heralding the approach of the next front. This pattern then repeats itself over and over with a series of fronts passing through the area in much the same manner as a series of waves wash past a buoy at sea. As with waves, the characteristics of passing fronts vary widely. Some advance very rapidly, while others may stall; some are wet, while others are dry; some lack wind, while others may spawn tornadoes.

## Summer

Typical summer weather pattern is usually dominated by the so-called Bermuda High, a more-or-less permanent high pressure cell which is centered in the Atlantic Ocean off the Carolinas. The gentle clockwise flow around this cell brings warm moist air to the entire eastern half of the nation. At Panama City, surface winds blow primarily from easterly and southeasterly directions. During the day, land areas are heated by the sun, causing the overlying air to warm, lighten, and ascend. A local sea breeze then sets in, causing the humidity to rise and local seas to become choppy. Rising air cools and condenses, forming cumulus and cumulonimbus clouds, which produce showers or thunderstorms practically every afternoon. Following sunset, these clouds usually dissipate, the sea breeze subsides, and local waters become smooth. This pattern then repeats itself day after day, broken only by the possible arrival of a tropical depression or hurricane from the trade wind belt.

## TEMPERATURE

Local air temperatures vary over a fairly wide range during the course of a year, with winter being the most variable period. As shown in Figure 5, mean daily temperatures vary from a low of 54.3°F (12.4°C) in January to a high of 81.9°F (27.7°C) in July. Summertime values generally range from 70 to 95°F (21.1 to 35°C), with occasional excursions into the high nineties (Reference 1). Wintertime values generally range from 45 to 75°F (7.2 to 23.9°C) with occasional dips into the low thirties. Cold weather intervals usually last only a few days, and while local air temperatures have dropped to as low as 10°F (-12.2°C) on one occasion, subfreezing temperatures are observed on fewer than 10 days of each year, and then only during early morning hours. Wintertime values as high as 80°F (26.7°C) have been recorded prior to the arrival of some cold fronts. The relatively warm waters of the nearby Gulf of Mexico exert a moderating influence on local air temperatures. Whereas readings from inland sites may be several degrees lower than coastal air during winter cold spells, slightly warmer temperatures can be expected over land than water during summer.

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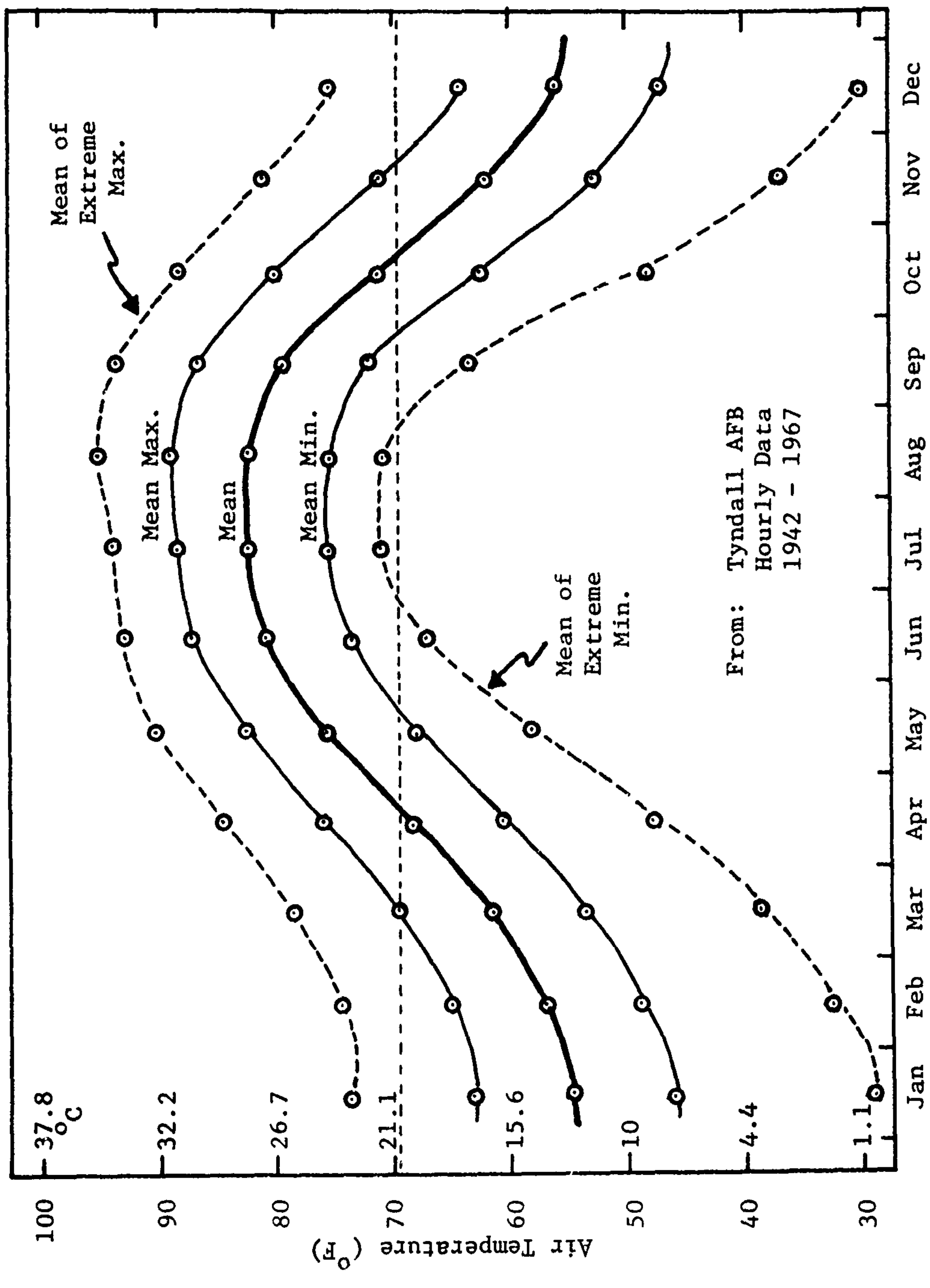


FIGURE 5. MEAN ANNUAL AIR TEMPERATURE CYCLE

PRECIPITATION

While hailstones have been known to fall out of severe thunderheads, and brief flurries of snow have been recorded during the passage of particularly severe cold fronts, rain is the only significant type of precipitation observed in the Panama City area. A total of 58 inches (147 cm) of rainfall can be expected during a typical year (Reference 8). Mean monthly values and the percent of days (per month) with rain are plotted in Figure 6. These curves show that May and October are usually the driest months, while July is the wettest (Reference 1). Distinctive summertime peak is caused by local shower activity, whereas a secondary peak in February and March is associated with the passage of frontal systems. Some years are drier than others. The least amount of rain was 41 inches (104.1 cm) in 1955; the most was 85 inches (215.9 cm) in 1959. The area has gone without any rain for periods of up to several months. The greatest amount to fall in a single month was 31.26 inches (79.4 cm) in July of 1898; greatest amount to fall in a single day was 8.83 inches (22.4 cm) on 31 August 1950 (Reference 8). One final characteristic of local rainfall should be noted. When it rains in Panama City, it literally pours; brief but heavy showers are far more likely to occur than an all-day drizzle. Thus, even though the area receives approximately 10 percent more rainfall than the northeastern states, it also receives about 10 percent more sunshine.

FOG

Fog occurs fairly frequently over local coastal waters during some periods. Historical records from nearby Tyndall Air Force Base reveal that fog occurs much more often during winter than summer. As shown in Figure 7, the percent frequency of occurrence of fog ranges from 10 to almost 15 percent during the months of December through March, but decreases to less than 1 percent during July and August (Reference 8). Preferred hours of occurrence are indicated in Figure 8, where it can be seen that fog is much more prevalent just before sunrise than it is during the day.

Advection Fog

The most common type of fog observed locally is advection fog, which forms whenever warm moist air flows over a cold water surface and is cooled to its dewpoint. Since coastal and bay waters are invariably cooler than central Gulf waters during the winter, fog can be expected whenever a south wind arises. This occurs prior to the arrival of cold fronts when the Panama City area is situated within a warm sector. Resulting fog may propagate many miles inland. Little is known regarding the distance offshore to which such fog banks extend. This type of

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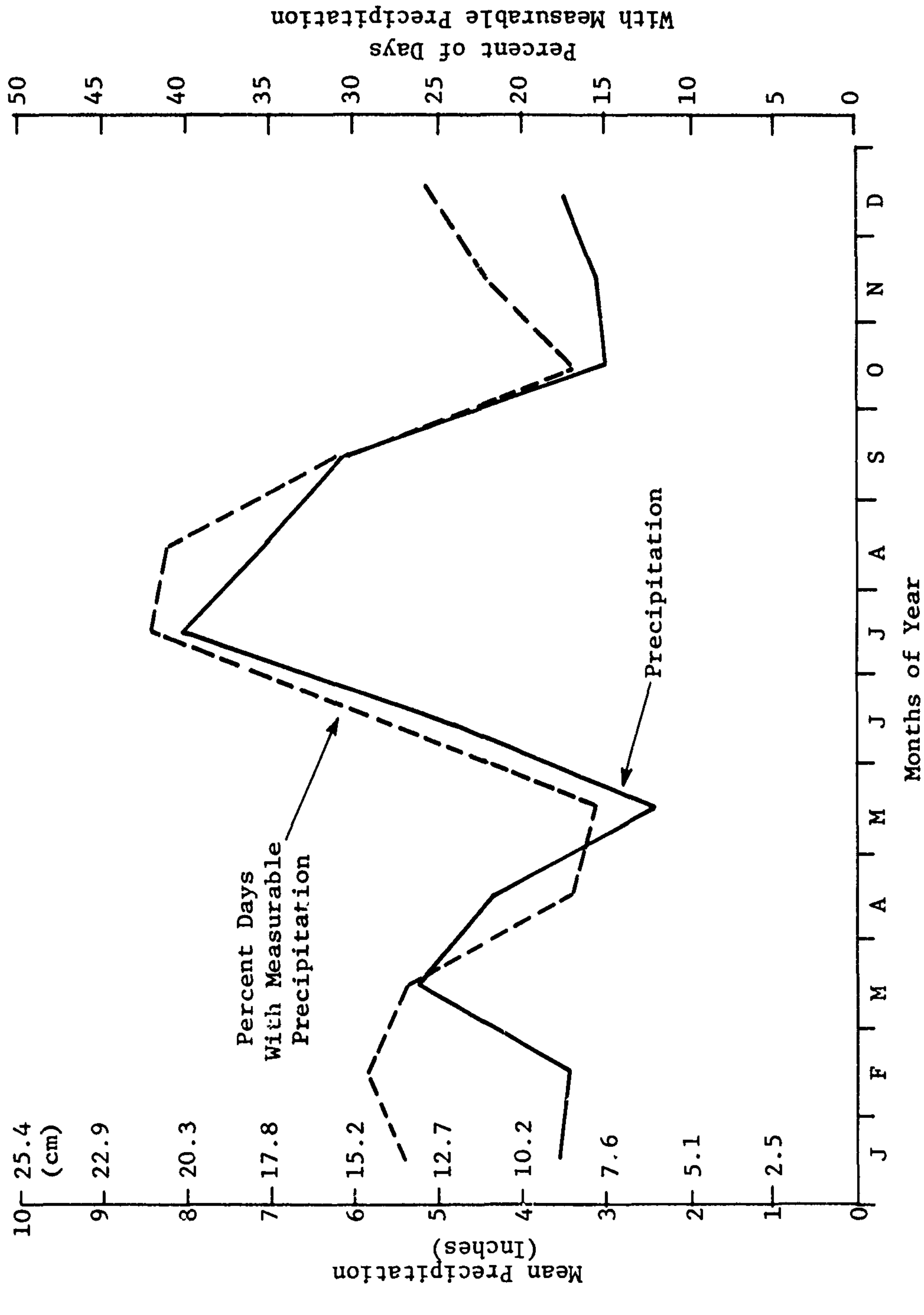


FIGURE 6. MEAN ANNUAL PRECIPITATION CYCLE IN PANAMA CITY AREA

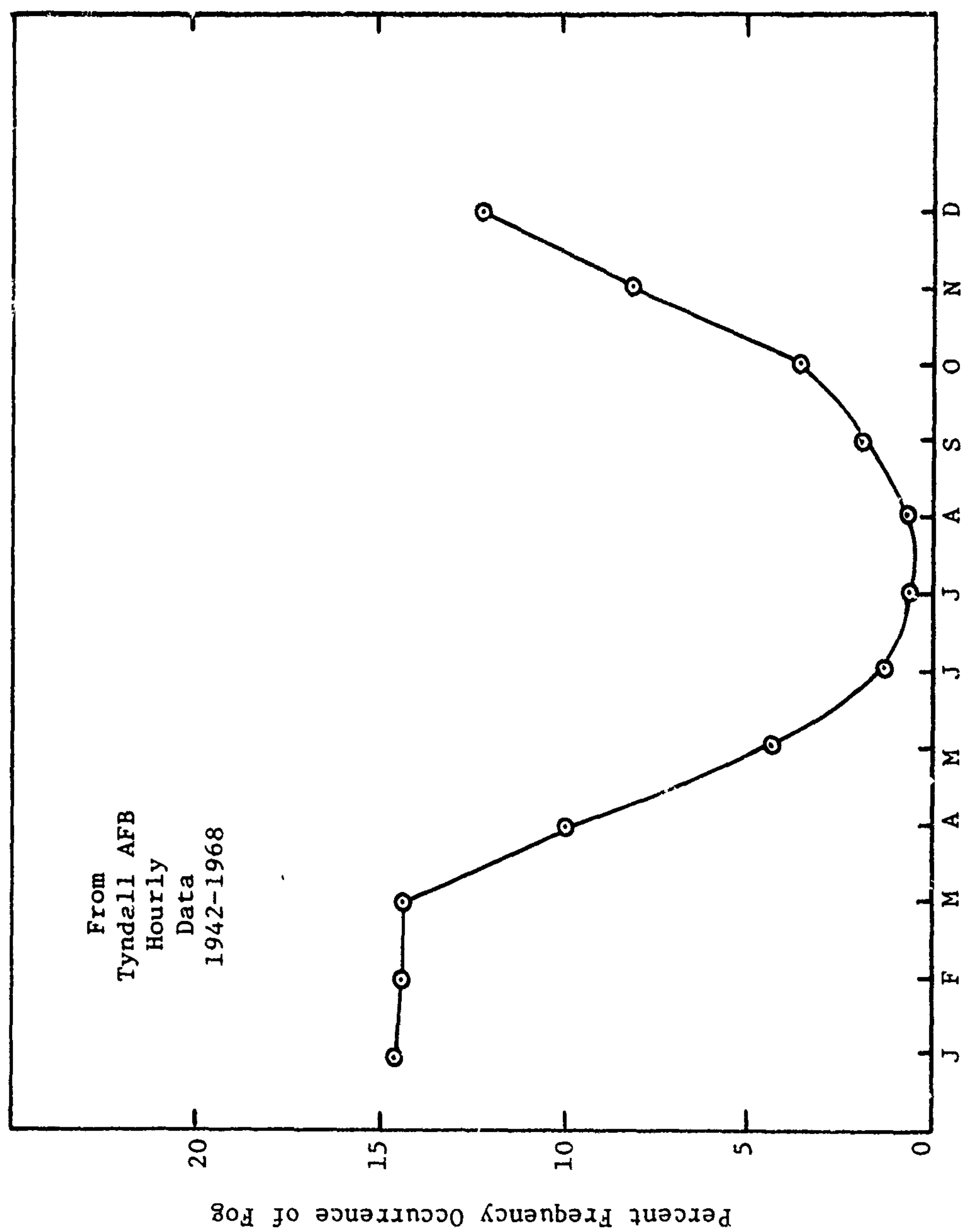


FIGURE 7. PERCENT FREQUENCY OF FOG BY MONTHS

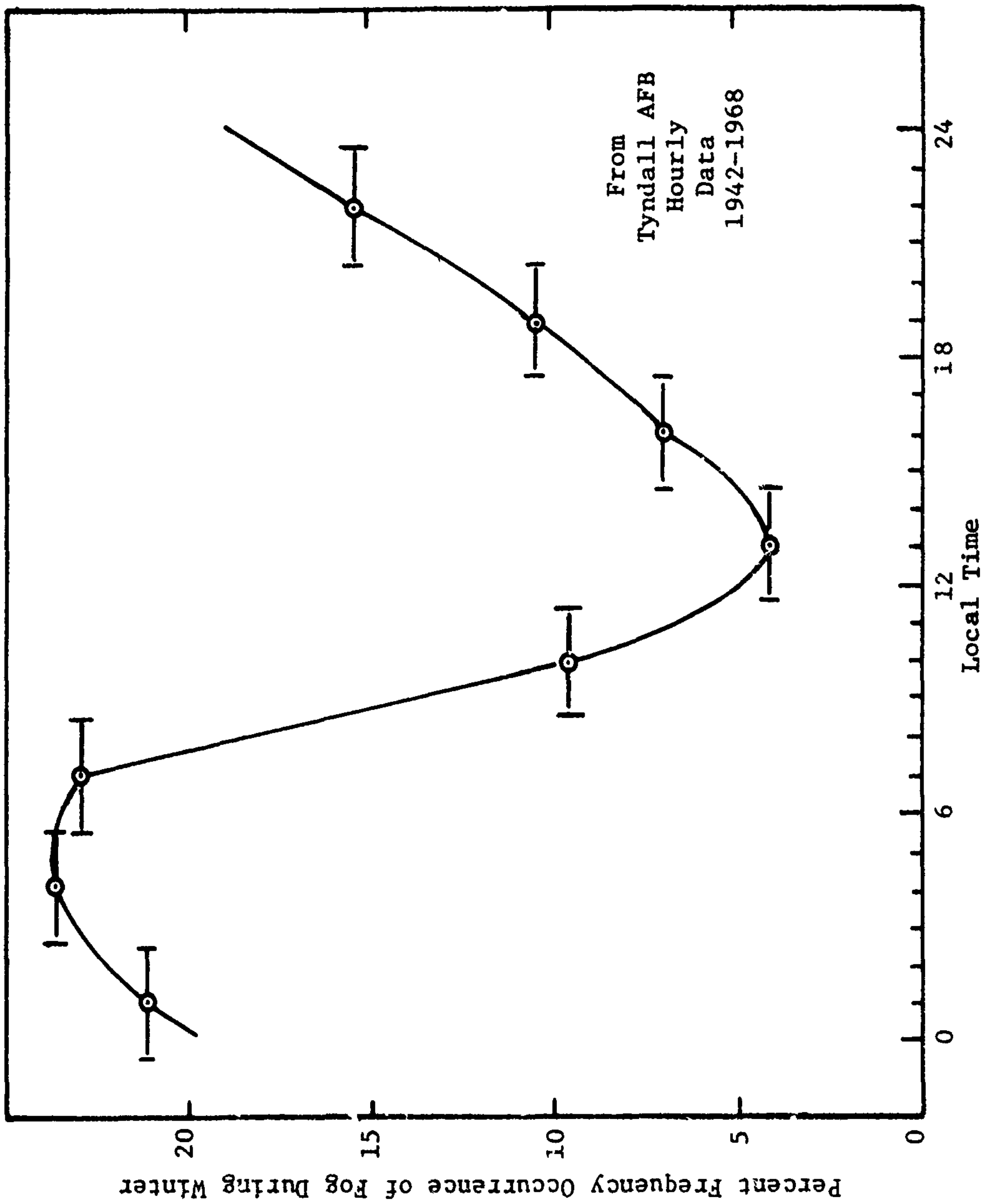


FIGURE 8. PREFERRED HOURS OF FOG OCCURRENCE

fog is usually thickest at night. If overlying cloud banks are not too thick, the sun generally causes fog over land to dissipate by 10 a.m., but portions over the cold inshore waters may persist through an entire day, ready to reinvade land areas after the sun sets. Reinvasion could take place earlier in the day if overlying clouds thicken or onshore winds strengthen. General foggy conditions persist as long as the area remains within a warm sector. Advection fog disappears when the associated cold front arrives, and does not reappear until another warm sector develops some days later.

### Radiation Fog

Radiation fog occasionally forms over local landmasses as air temperatures plummet during clear cold nights. This type of fog lies close to the ground, tends to accumulate in low spots, is generally thickest just before sunrise, and usually dissipates by midmorning as air temperatures rise. Another type of fog, known as "Arctic sea smoke," has been observed over local waters whenever extremely cold air invades the area from the north. The warm sea surface then appears to be smouldering as it transfers moisture to the atmosphere. Fortunately, this type of fog is never very thick, and is seldom observed more than two times in an entire winter.

## WINDS

Historical weather records from nearby Tyndall Air Force Base (Reference 8) reveal that local winds are characteristically weak, seldom amounting to more than a gentle breeze. A long-term wind speed histogram is presented in Figure 9. Based on a total of 233,321 hourly observations spanning 27 years (1942 to 1968), this histogram shows that the frequency of occurrence of winds of 7 to 11 knots is approximately 32 percent, that of winds of 4 to 7 knots is about 24 percent, and that of winds 11 to 17 knots is about 15 percent. Speeds greater than 22 knots can be expected only about 1 percent of the time. As shown in Figure 10, the annual frequency of calms is approximately 13 percent, with calms occurring most frequently in August (19.8 percent) and least frequently in March (8.6 percent). Winds are generally lighter at night than during the day, especially during summer. Cold fronts sometimes bring winds of 25 to 35 knots to the local coastal area, but these strong winds do not usually persist for more than 12 hours. Brief gusts as high as 60 knots have been recorded during occasional severe thunderstorms. Only during hurricanes is the local coastal area swept by winds of greater strength. Beaches to the west of St. Andrew Bay were buffetted by winds of up to 100 knots (estimated) for a period of several hours during the passage of Hurricane ELOISE on September 23, 1975. Fortunately, hurricanes of this magnitude do not visit the local area very frequently. General expectancy is only one major storm every 10 to 15 years.

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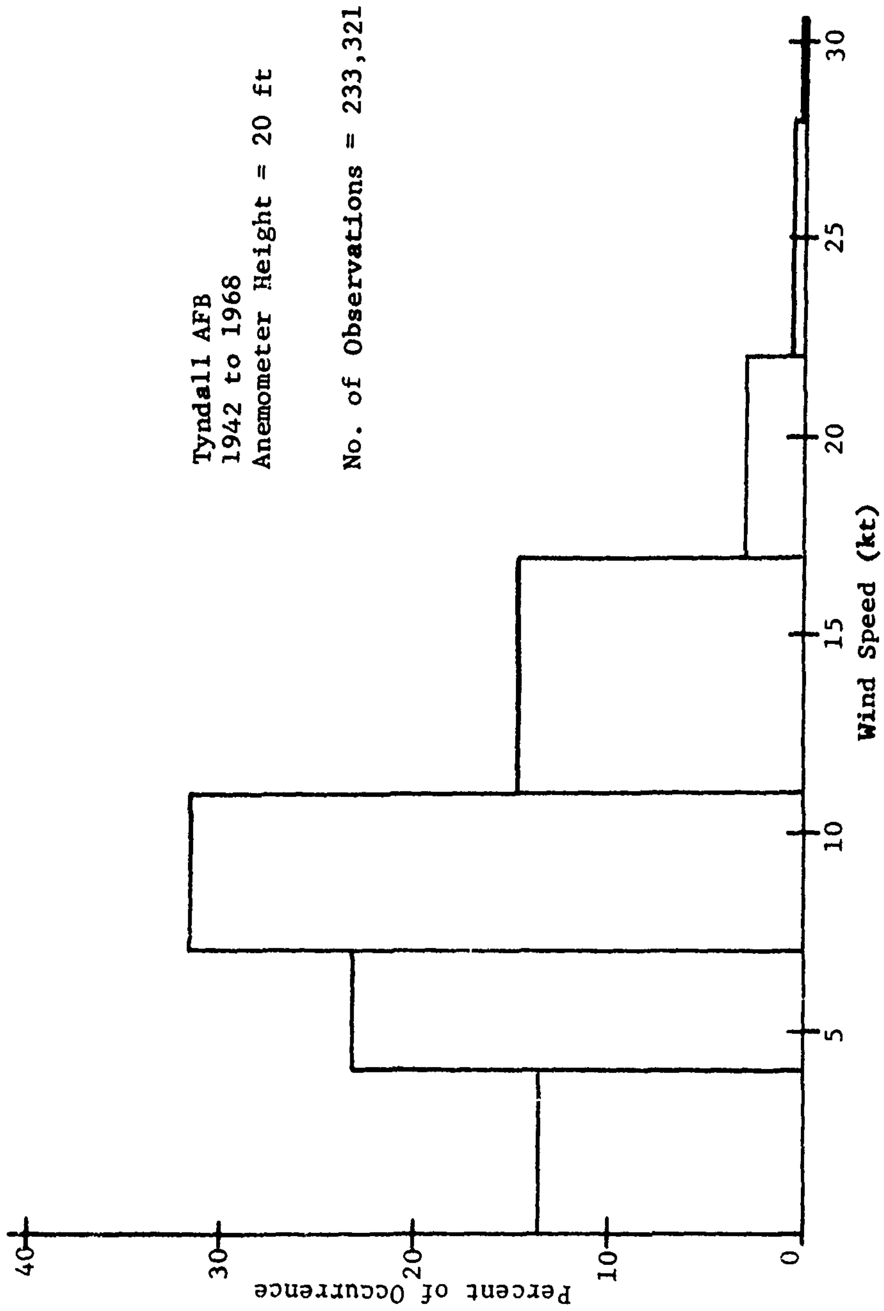


FIGURE 9. HISTOGRAM OF WIND SPEEDS

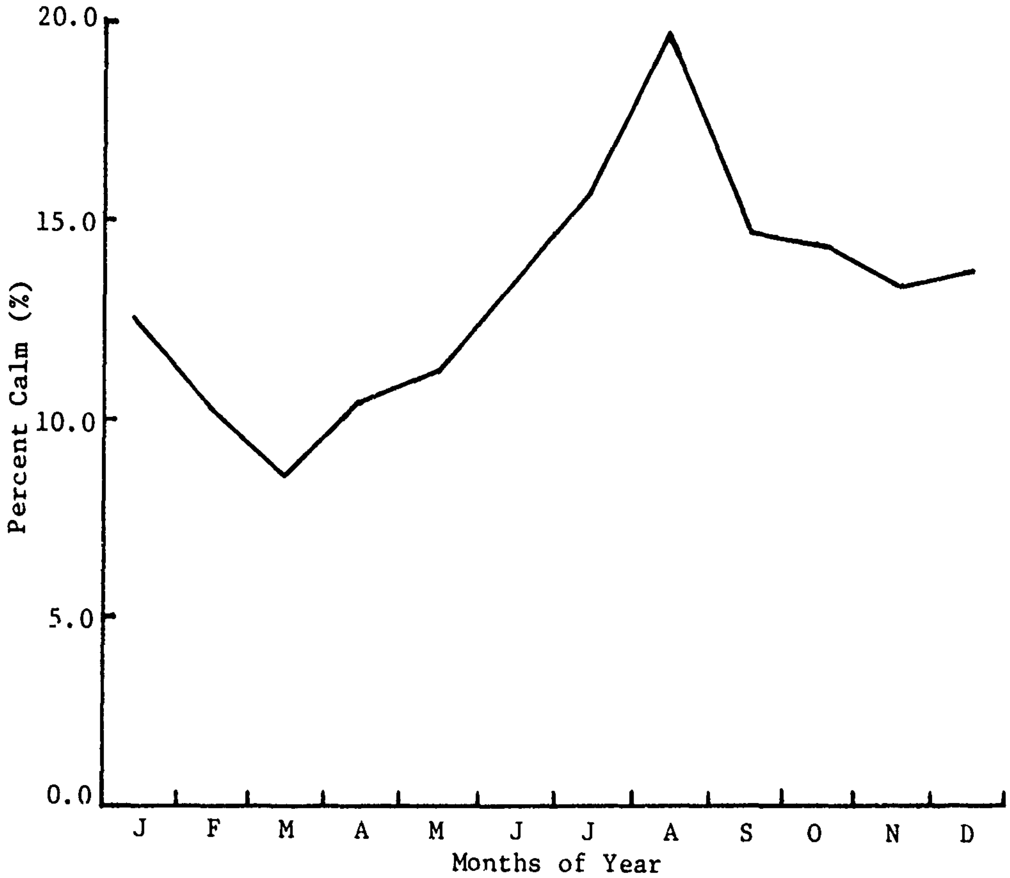


FIGURE 10. FREQUENCY OF CALM WINDS

A seasonal pattern is evident in the monthly wind direction plots presented in Figure 11 (References 8 and 9). The left hand set of plots is for all wind speeds; the right hand set is for winds in excess of 10 knots. Numbers appearing on vertical axes are percent frequencies. Comparison of successive monthly plots reveals a gradual reduction in the frequency of occurrence of northerly winds during first half of year, followed by a gradual increase during second half as frontal passages become more numerous. Winds blow from southeasterly quadrant more frequently during winter and early spring than during summer and early fall (this is especially noticeable in the right hand plots in Figure 11). These peaks are caused by pre-frontal winds. Another distinctive peak shows up in the southwest quadrant during summer months (this is especially noticeable in the left hand plots in Figure 11). Daytime sea breeze is the primary cause of this peak. Likelihood of onshore winds is greatest from May through August; likelihood of offshore winds is greatest from September through January. Effects of these seasonal changes on local wave action, tides, and currents are discussed in subsequent sections.

## SEA SURFACE CONDITIONS

### WAVES

Surface wave records from NCSC's offshore research platforms and other nearby sites reveal that local coastal waters are relatively placid most of the time, but that waves of appreciable magnitude are generated whenever passing frontal systems or hurricanes bring strong winds to the area. A seasonal pattern is quite evident in Figure 12. This wave height expectancy diagram shows that higher sea states are much more likely to be encountered during winter than summer. While waves greater than 3 feet in height can be expected only 18 percent of the time during July, they can be expected over 50 percent of the time during December. This diagram also shows that waves greater than 8 feet in height are usually encountered only during winter months. Large waves can also be expected during summer months if the local area comes under the influence of a tropical storm (Reference 3). The Panama City area was subjected to waves with heights of up to 30 feet (estimated) during Hurricane ELOISE on 23 September 1975. Fortunately, storms of this type do not usually remain in an area for more than a day or two, and there are many years during which no hurricanes are observed in the Gulf of Mexico. Thus, from a statistical point of view, the warm weather months must be regarded as a period of relatively quiescent seas.

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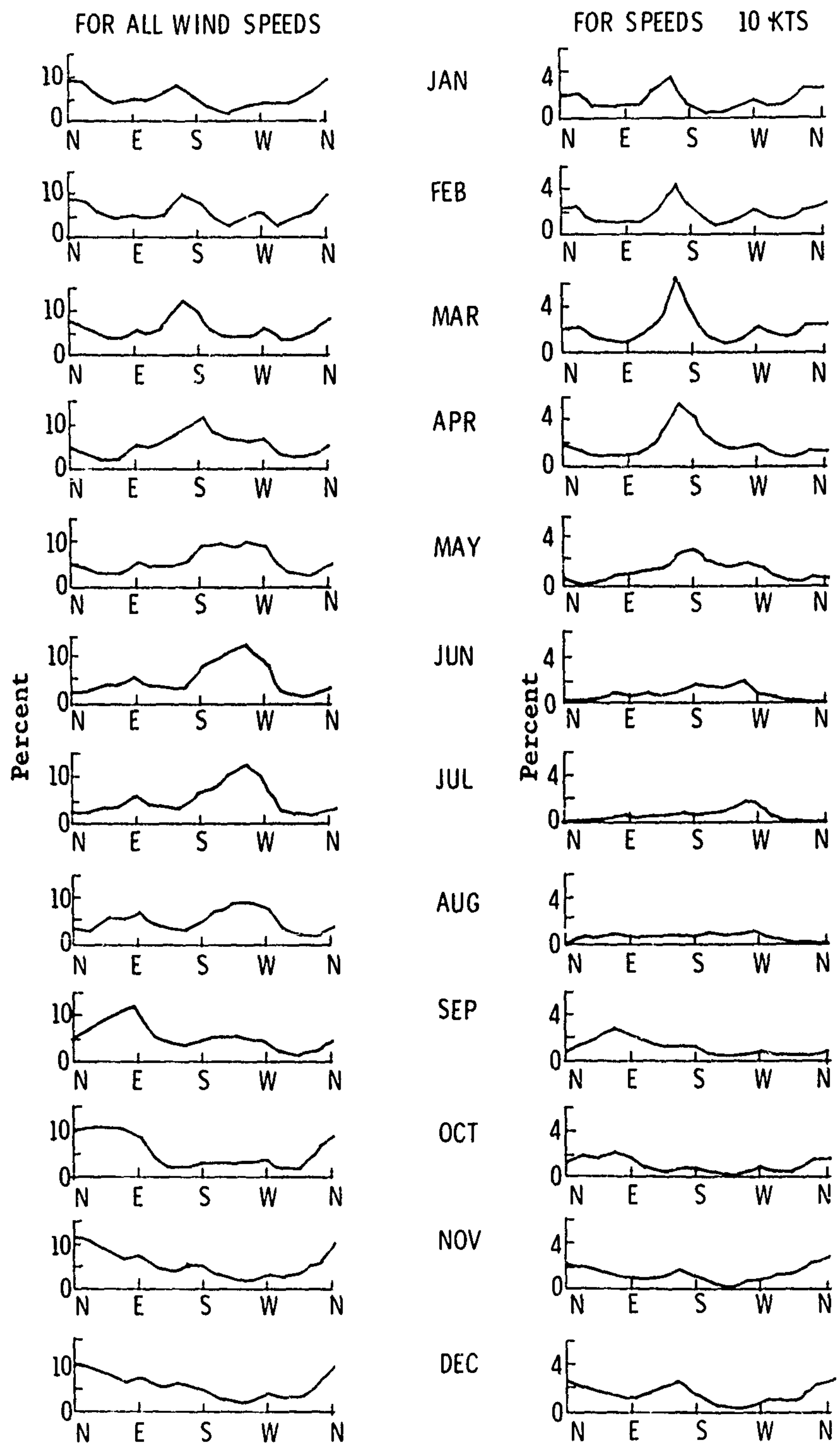


FIGURE 11. MONTHLY WIND DIRECTIONS AT PANAMA CITY

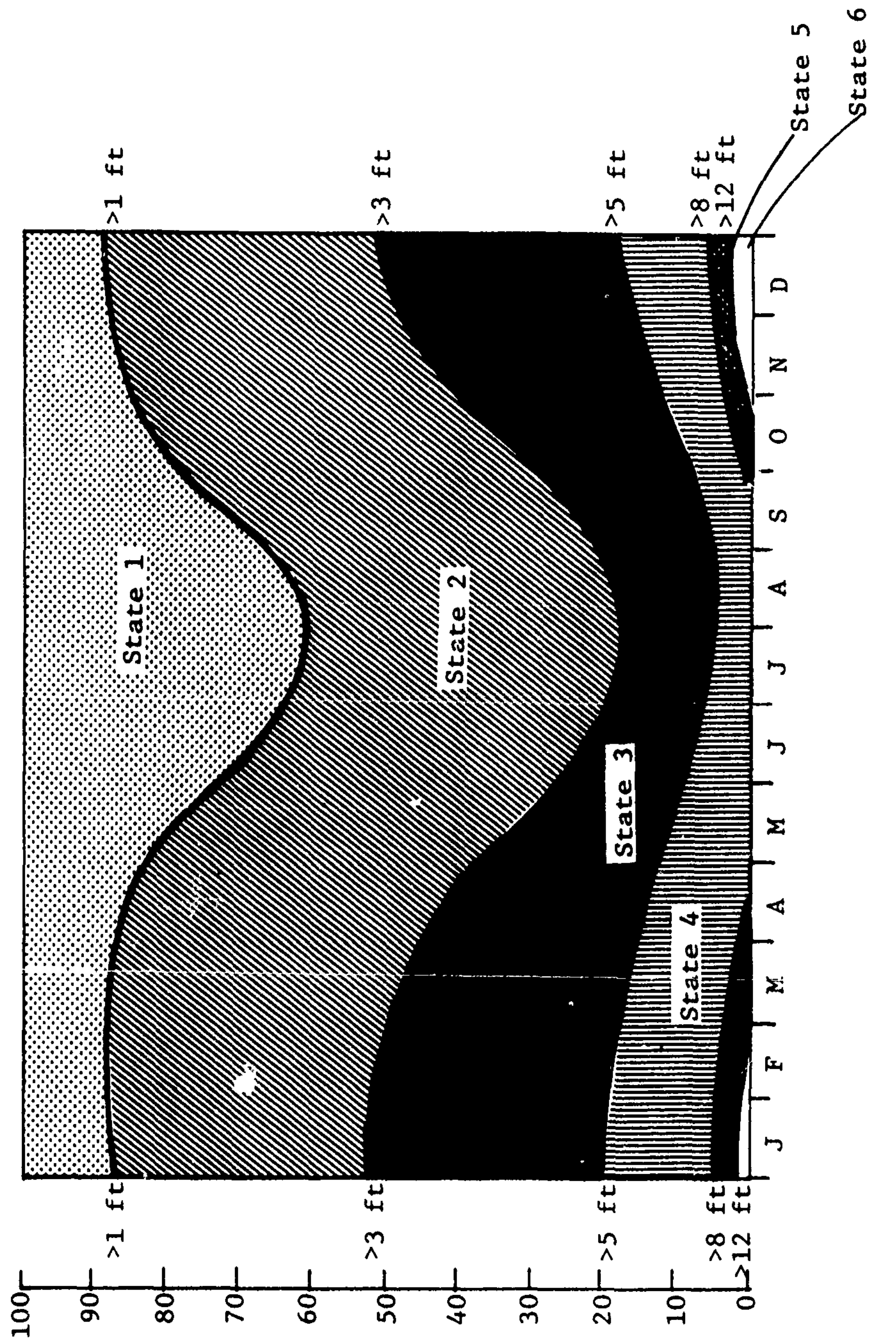


FIGURE 12. EXPECTED WAVE HEIGHTS AT PANAMA CITY

Examples of wave height variability during selected meteorological situations are provided in Figures 13 through 16. The changes in significant wave heights at Stage I during the passage of both typical and severe cold fronts, as well as the low seas which prevailed during an extended front-free wintertime interval are shown in Figure 13. A typical summer record is presented in Figure 14. The increased wave activity which accompanied the summertime passage of an easterly wave (atmospheric) is shown in Figure 15. A record of the heavy wave action at deep-sea buoy EB-10 located 185 miles southwest of Panama City during the passage of Hurricane ELOISE is presented in Figure 16. These examples show that wave heights vary considerably in local coastal waters, not only from one season to another, but within the same season. In fact, radical departures from long-term seasonal norms may occur at any time. It is thus possible for local seas to be flat on a winter day, or to be tumultuous on a summer day. Records also show considerable variability from one year to another, and from one hour to another. Local wave heights are generally higher during afternoons than early morning, especially during intervals when the sea breeze is well developed. Then too, heavier wave action is usually reported from Stage I (12 miles (19 km) offshore) than Stage II (1.5 miles (2.4 km) offshore), especially during post-front periods when fetch-limited northerly winds prevail. Few waves are observed on local beaches whenever the wind blows from the northeastern quadrant. Additional statistics regarding local wave conditions are in Reference 3.

Three examples of surface wave spectra from local coastal waters are provided in Figures 17 through 19. The spectrum depicted in Figure 17 was obtained during a period of relatively quiet seas. Significant wave height was less than 2 feet, and most of the wave energy was concentrated in a single peak (centered near frequency of 0.2 hertz) produced by small wind-generated waves with a period of approximately 5 seconds. The spectrum depicted in Figure 18 was obtained during a period of relatively heavy seas. Significant wave height was almost 9 feet, energy levels were considerably higher than in previous example, and two distinctive peaks were evident. Highest peak was associated with locally-generated wind waves of relatively short period (2 to 6 seconds); secondary peak (centered near a frequency of 0.1 hertz) was produced by ocean swells with a period of approximately 10 seconds. Dual peaks of this type are often encountered whenever meteorological disturbances are present in other parts of the gulf as well as in the local area. In some cases, a peak associated with local wind waves is larger than a peak associated with swells; but swell-dominated spectra have also been obtained from local waters (Figure 19).

The wave spectra shown in Figures 17 through 19 are examples of several recently acquired records and should not be considered typical for Panama City waters. Other examples are provided in References 3 and 10. Pidgeon and Pidgeon (Reference 3) have examined many wave spectra

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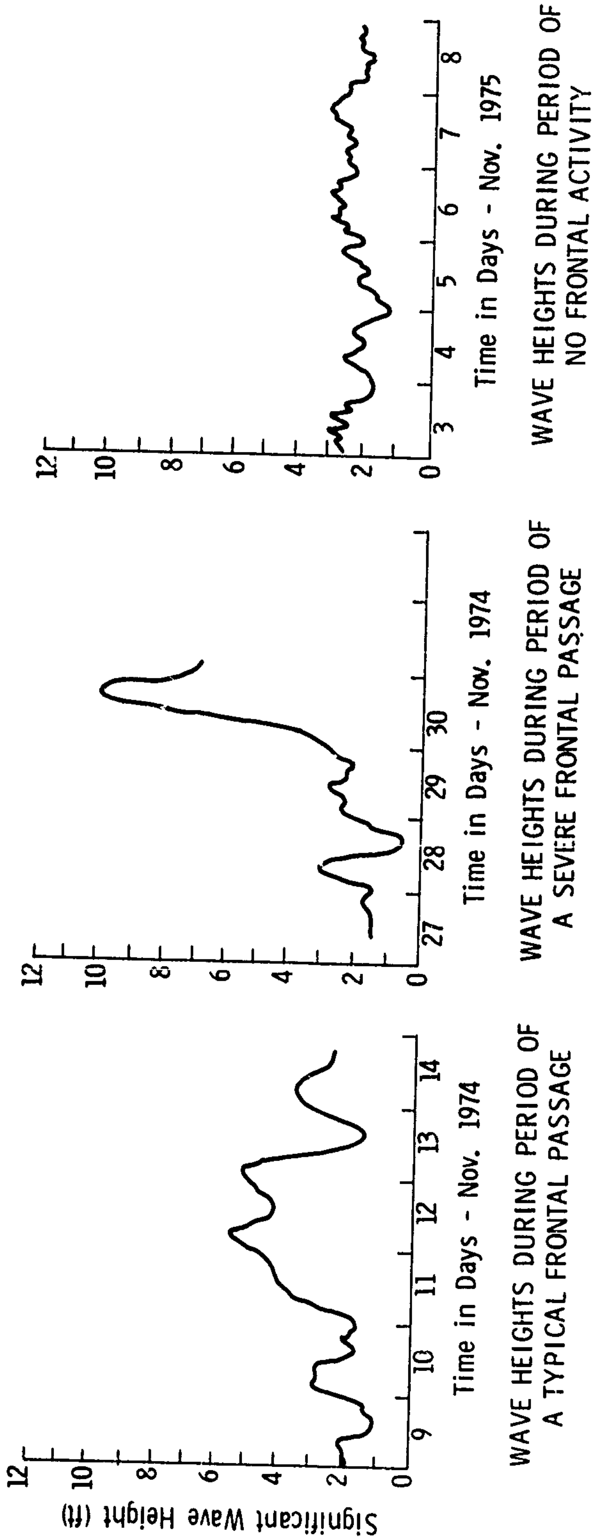


FIGURE 13. WAVE HEIGHTS DURING WEATHER FRONTS

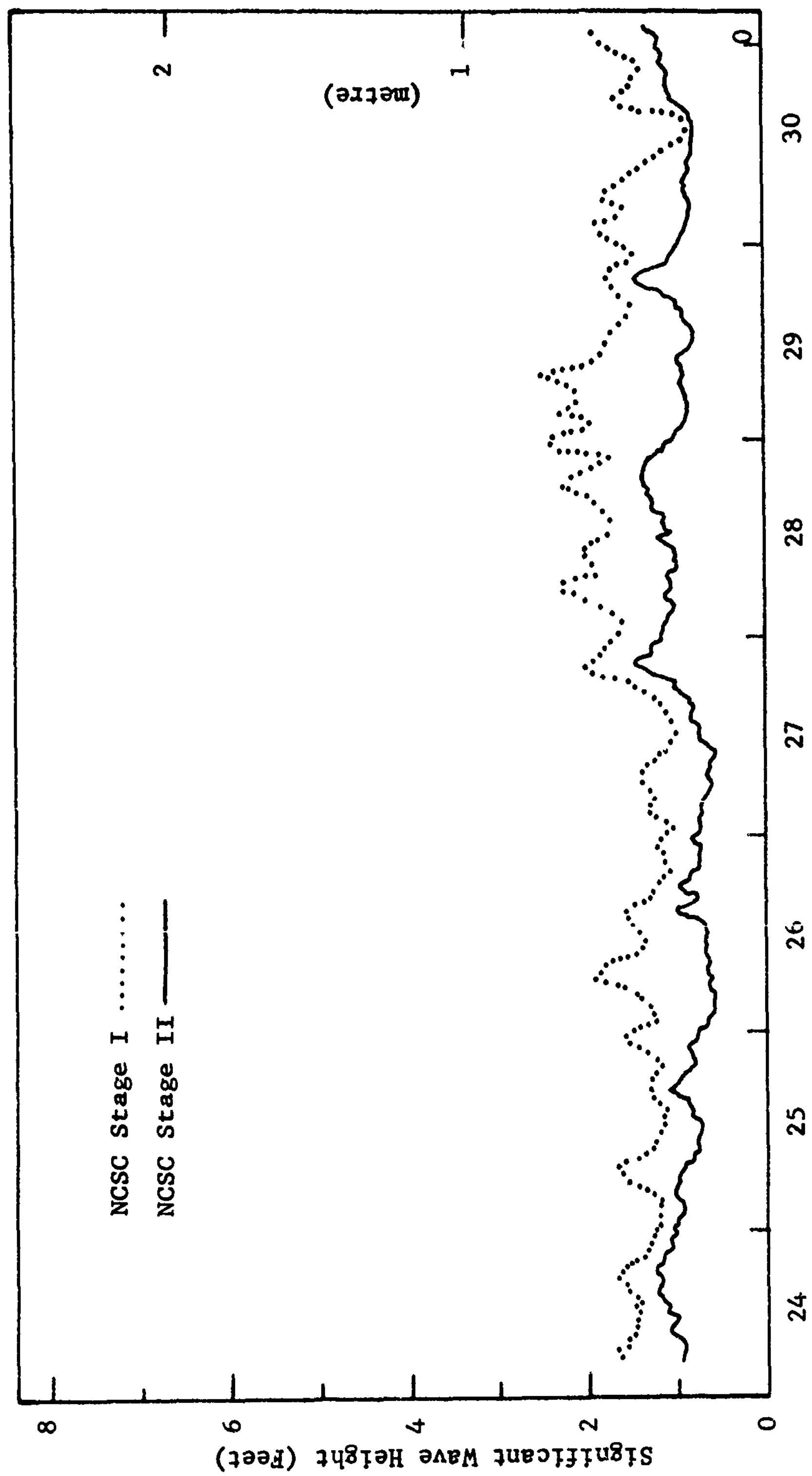


FIGURE 14. WAVE HEIGHTS DURING TYPICAL SUMMER WEATHER

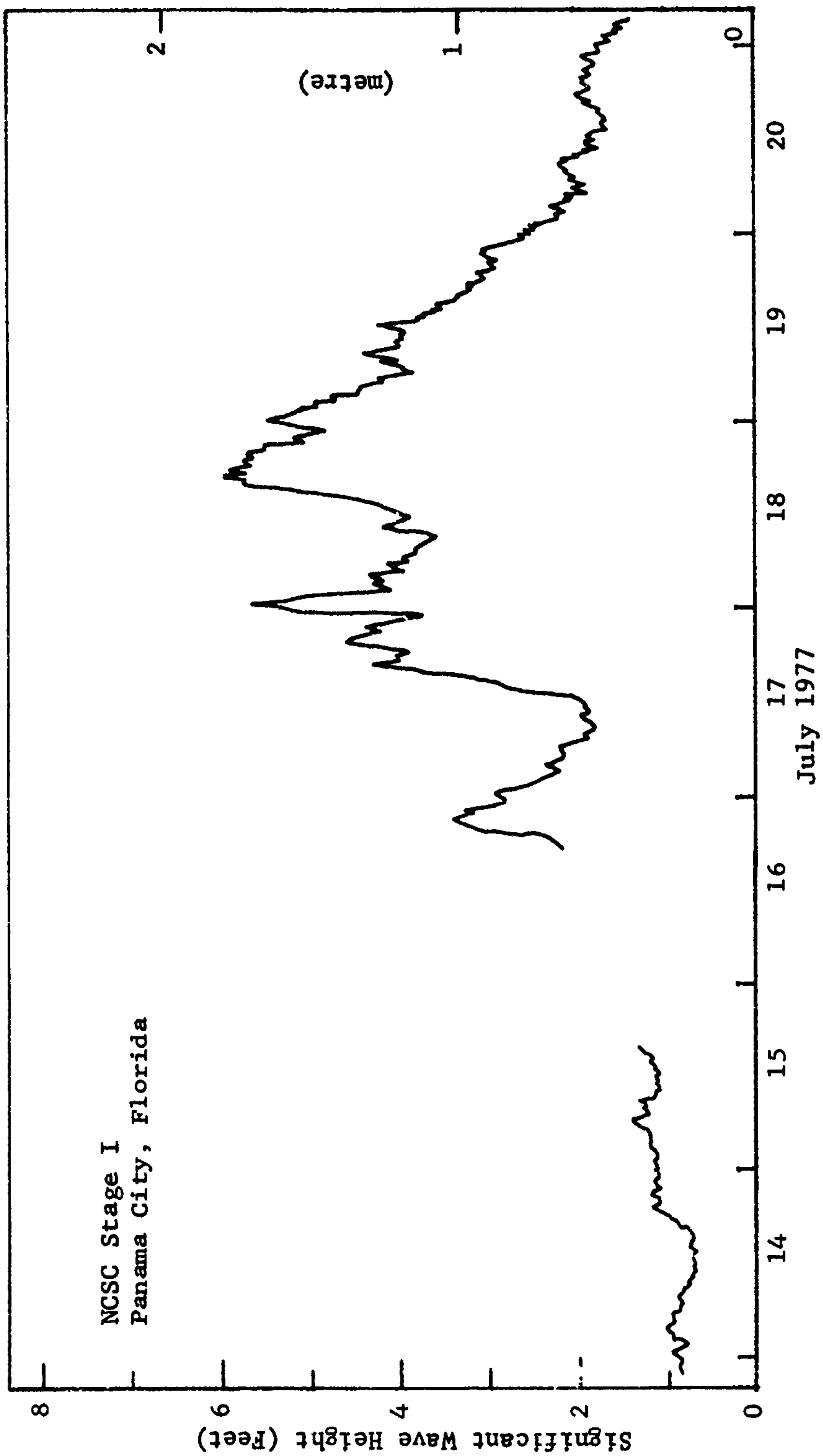


FIGURE 15. WAVE HEIGHTS DURING PASSAGE OF EASTERLY WAVE

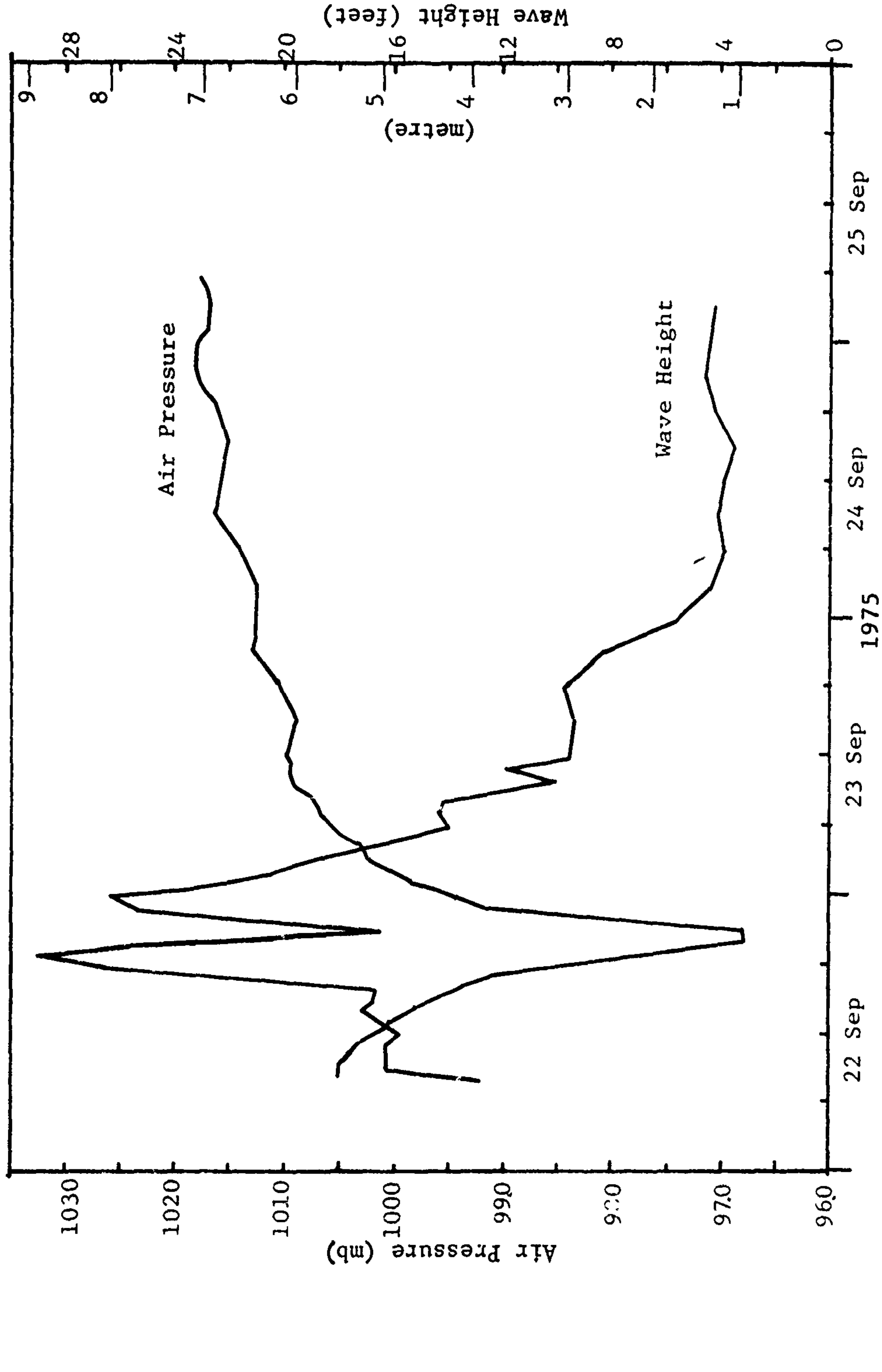


FIGURE 16. WAVE HEIGHTS AND AIR PRESSURE AT DEEP SEA BUOY EB-10 DURING HURRICANE ELOISE

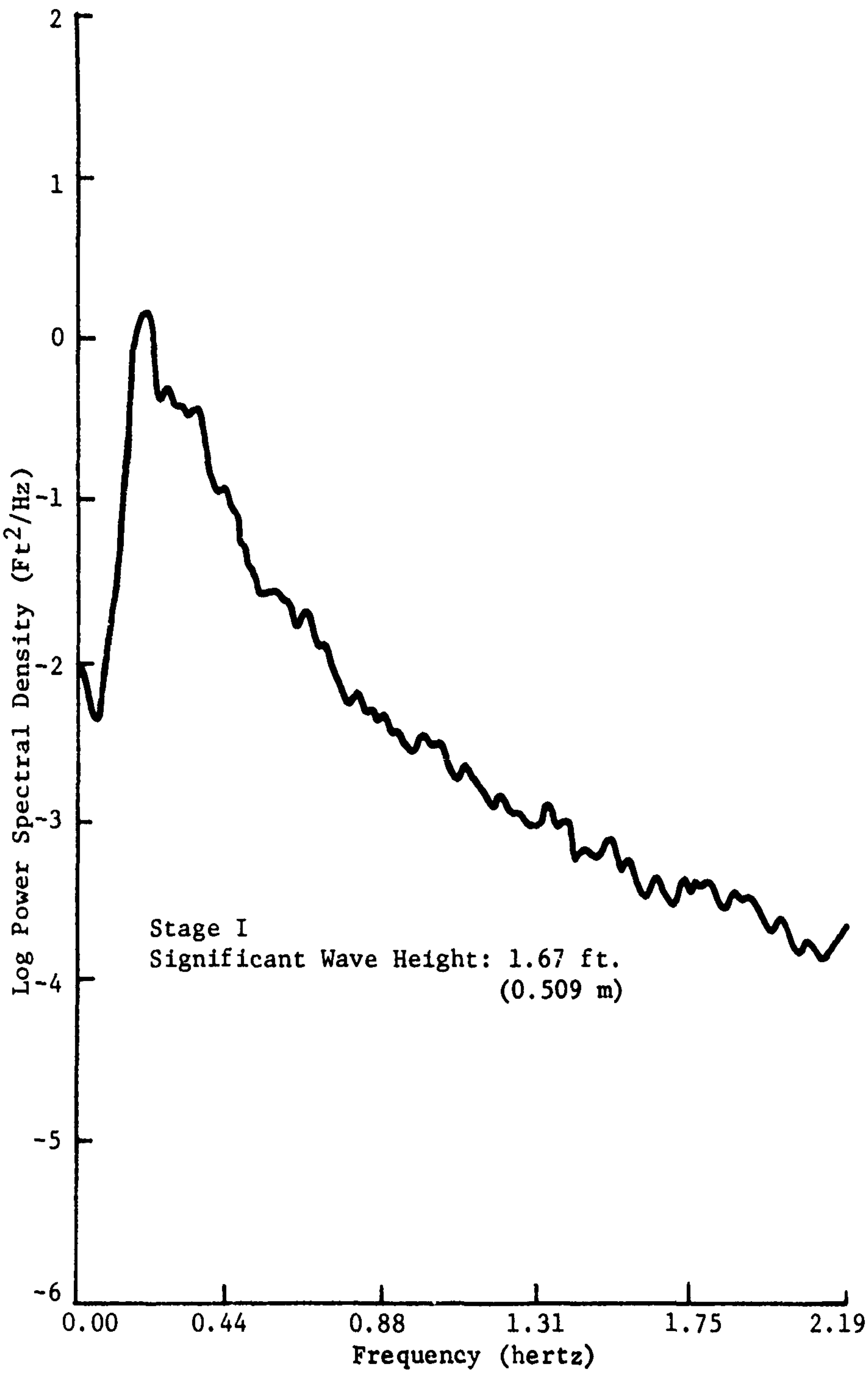


FIGURE 17. LOW ENERGY WAVE SPECTRUM AT STAGE I

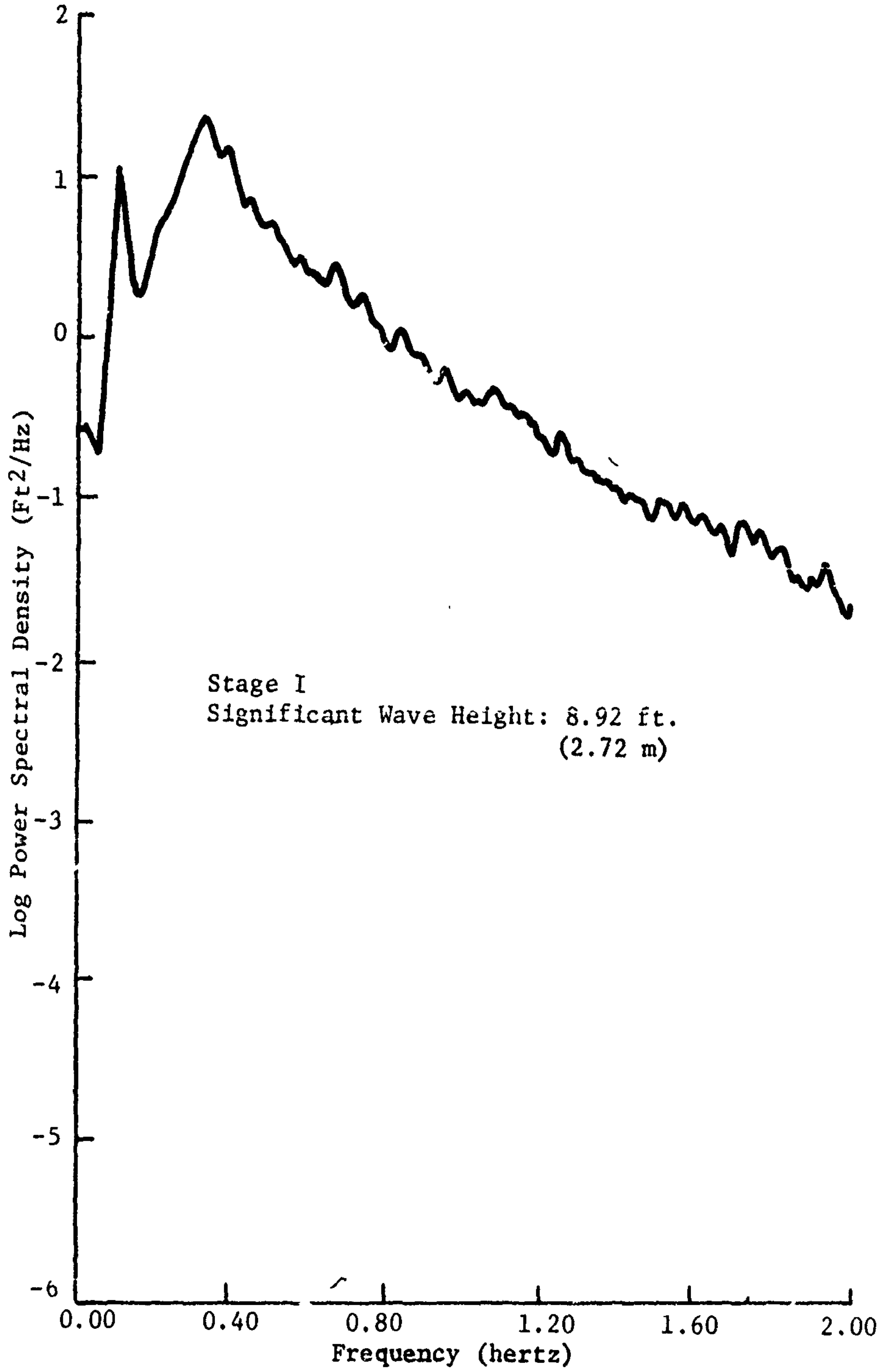


FIGURE 18. HIGH ENERGY WAVE SPECTRUM AT STAGE I

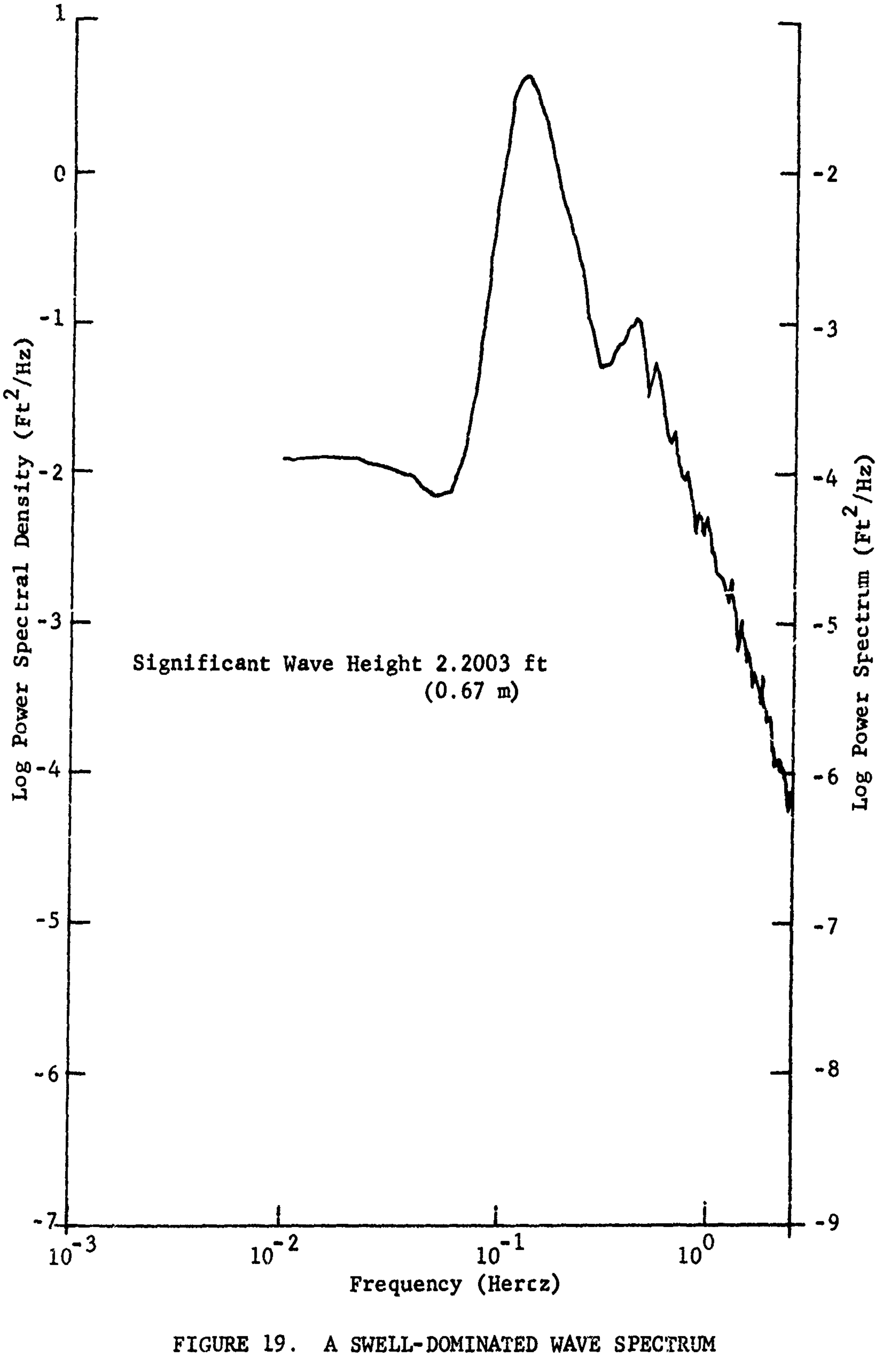


FIGURE 19. A SWELL-DOMINATED WAVE SPECTRUM

from local waters, and have noted considerable variability, not only in terms of shape, number, position, and relative size of peaks, but also in terms of total energy related to significant wave heights. Additionally, they point out that the peak frequencies observed in local wave spectra are almost always less than theoretical values predicted by the classic Pierson-Neumann-James method (Reference 11), and they suggest this disparity may be linked to the fact that local seas seldom become "fully arisen"--a state of equilibrium wherein a given wind field of constant speed, direction, and fetch has caused waves to build up to some maximum size and grow no further even if the wind persists. Area winds vary so much in both speed and direction, that the local sea surface is in a constant state of re-adjustment. This is especially true of winds blowing offshore, where only slight changes in direction lead to dramatic changes in fetch length. Consequently, part of the available wind energy is spent reforming waves produced by earlier winds, and the resultant waves are not as large as those which would have accompanied winds of more uniform velocity.

Despite the above mentioned variability, certain generalizations can be made regarding the spectral characteristics of local coastal waters. If fair weather prevails over the entire gulf, spectral energy levels are low and a single peak is usually present in the 0.2 to 0.5 hertz frequency band corresponding to wave periods of 2 to 5 seconds. Meteorological disturbances arising in other parts of the gulf usually cause a secondary peak to develop within 24 hours, and this peak may dominate the record if local winds remain weak. But if the local area receives strong southerly winds, such as prior to the arrival of a cold front, spectral energy levels will increase rapidly as waves of various frequency enlarge. Two or more peaks may then appear. The highest peak is usually centered in the wind wave band (with periods of 2 to 6 seconds), while others are centered in the swell band (with periods of 7 to 10 seconds). Wave periods may increase to as much as 12 to 14 seconds if a hurricane brings violent winds from offshore. But the strength and rate of movement of frontal systems and tropical storms are highly variable, especially in the so-called horse latitudes; hence considerable difference must be expected in wave spectra obtained during the passage of each front or tropical storm. Spectral peaks subside rapidly after storms pass, with energy levels and frequencies usually returning to normal within 36 hours of storm's departure.

Within St. Andrew Bay, wave action is usually limited to short period wind waves with heights of less than 1 foot (0.3 m). During severe storms, however, waves may build to heights of 2 to 4 feet (0.6 to 1.2 m) near the downwind end of long reaches. Waters adjacent to leeward shores and within narrow bayous remain relatively calm, even during windy periods. The bay surface becomes especially choppy in areas where strong surface currents are set against a brisk wind. This condition is often encountered near bay entrances during outgoing tides.

Waves dissipate rapidly as the wind subsides. The surface of the bay will flatten completely in less than an hour if no wind is blowing. On many days, the only significant waves observed within the bay are those generated by passing vessels.

## TIDES

Local tidal oscillations, like those at most Gulf Coast sites west of the Apalachicola River, are chiefly diurnal in period, small in amplitude, and very susceptible to modification by wind and weather (References 12 and 13). A typical monthly prediction curve is presented in Figure 20. Only one high water and one low water are observed on most days. The difference in elevation between successive high and low waters is generally less than 2 feet (0.6 m). Mean tide range at Panama City is only 1.3 feet (0.4 m) (Reference 14). Tide takes approximately 14 hours to rise, and 11 hours to fall, completing each such cycle in a lunar day (24.8 hours).

A fortnightly variation in tide range is also evident in Figure 20. Daily ranges decrease to less than 0.2 feet (0.06 m) during intervals when the moon is on or near the celestial equator (called Equatorial tides), and increase to 1.5 to 2.5 feet (0.5 to 0.8 m) during intervals when the moon hovers over the Tropic of Cancer or the Tropic of Capricor (Tropic tides). Local tides are thus controlled primarily by lunar declination rather than lunar phase (new moon, first quarter, full moon, last quarter), whereas the opposite is true of tides in the Atlantic Ocean. The classic Atlantic concepts of spring and neap tides are thus of little use to local mariners.

Other astronomical factors which influence local tides are changes in solar declination and in the distance of moon and sun from the Earth. As shown in Figure 21, local tide ranges are slightly greater than normal during periods when solar declination is large (as during summer anc winter solstices), and are somewhat less than usual during periods when solar declination is small (as during vernal and autumnal equinoxes). Similarly, local ranges increase when the moon and sun get closer to thi Earth, and decrease as they recede. Additionally, local ranges become larger than normal during years when the inclination of the moon's orbi to the equator is greatest and become smaller than usual during years when this inclination is least (Reference 12). Duration of this long-term cycle is 18.6 years. Last such maximum occurred during the year 1969; next will occur in 1987. Last such minimum was in 1960; next wil occur in 1978. A tide range of up to 3 feet (0.9 m) can be expected in local waters if the moon and sun simultaneously achieve maximum souther declination and minimum distance from Earth during a year of maximum nodal nclination.

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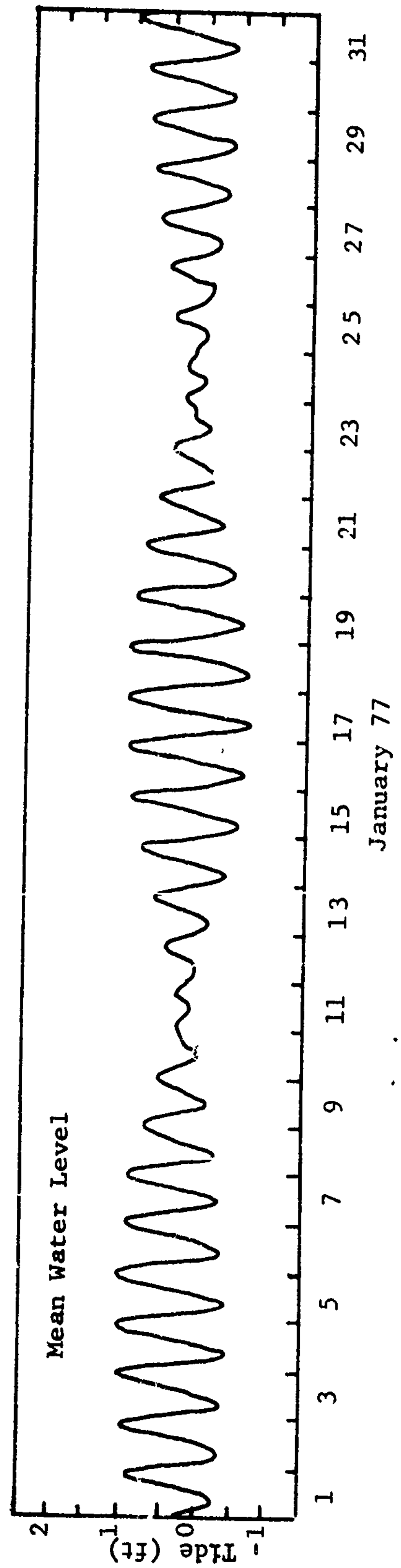


FIGURE 20. PREDICTED TIDES AT PANAMA CITY

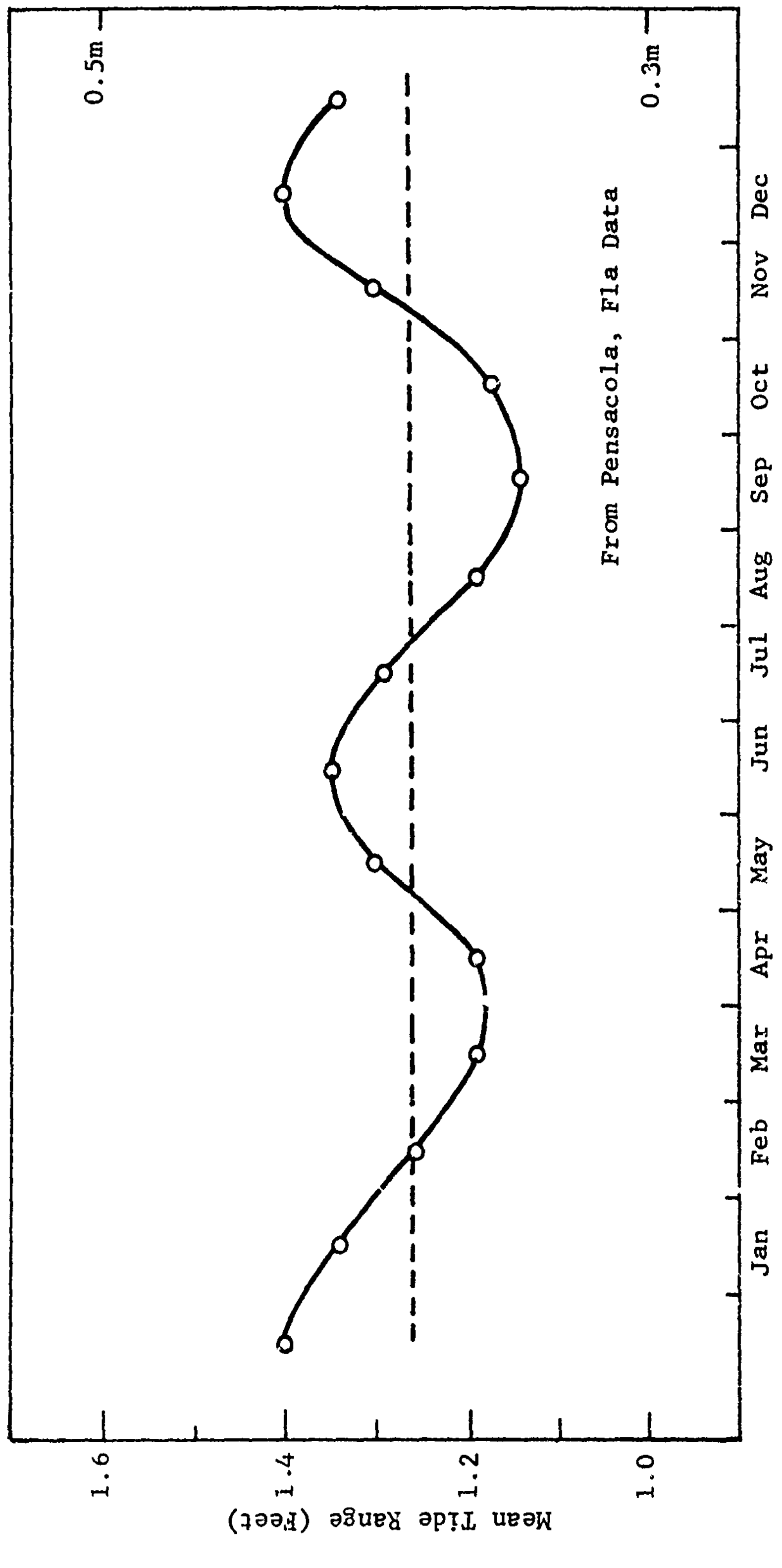


FIGURE 21. ANNUAL VARIATION IN TIDE RANGE

Still another variable factor is the level about which local tides oscillate. As shown in Figure 22 (Reference 12), water levels in the northeastern part of the Gulf of Mexico are almost 0.8 feet (0.2 m) higher during September than during February. The annual curve dips steeply during late fall and early winter, remains low during January and February, rises during the spring to an early summer plateau, then climbs to a maximum in September. While the causes of this annual variation have never been fully explained, changes in wind and weather are at least partly responsible. Winter time cold spells bring high pressure and northerly winds, both of which tend to lower water levels along northern gulf shores; and late summer tropical storms bring low pressure and southerly winds, both of which tend to raise local water levels. In addition to the observed annual sea level cycle, the mean elevation of the local sea surface (relative to coastal benchmarks) is seldom the same from one year to the next. Changes occurring at Pensacola from 1924 through 1971 are depicted in Figure 23 (Reference 15). Appreciable year-to-year fluctuations are evident in this record. A rise of approximately 0.5 feet (0.15 m) occurred during the first half of observation period, but levels have remainded essentially stationary since 1950. Scientists have been unable to establish whether these changes were caused by an actual rise in sea level, by subsidence of coastal landmass, or by a combination of both.

Several other features of the local tide regime should also be mentioned. The tide ranges generated by astronomical forces are relatively small, and are hence very susceptible to modification by meteorological forces. Effects of wind are particularly noticeable. Strong northerly winds following the passage of a cold front have been known to lower water levels in St. Andrew Bay as much as 4 feet (1.2 m) below normal, temporarily exposing many shallow sand bars and mud flats. Conversely, if strong southerly winds precede the arrival of a cold front, water levels in the bay may rise as much as 2 feet (0.6 m) above normal. The extra-strong southerly winds generated by Hurricane ELOISE in 1975 caused the bay surface to rise 4 to 5 feet (1.2 to 1.5 m) above normal, temporarily flooding many low-lying areas. The Corps of Engineers contend that waters rose as much as 16 feet (4.9 m) above normal along gulf-front beaches close to ELOISE'S central track (Reference 16).

Times of high and low waters are also subjected to considerable change during periods of inclement weather. Under normal conditions, it takes approximately 1 hour for the crest of the tide wave to make its way from the bay entrance up to NCSC, and another 1 to 2 hours to reach the upper ends of the bay system. But strong southerly winds may cause the bay to fill much more rapidly than ususal, and to remain high for many hours. Conversely, strong northerly winds tend to empty the bay more rapidly than usual, and cause it to remain low for many hours. Sudden changes in wind velocity or air pressure have also been known to induce seiches within the various arms of the bay system. Periods of these

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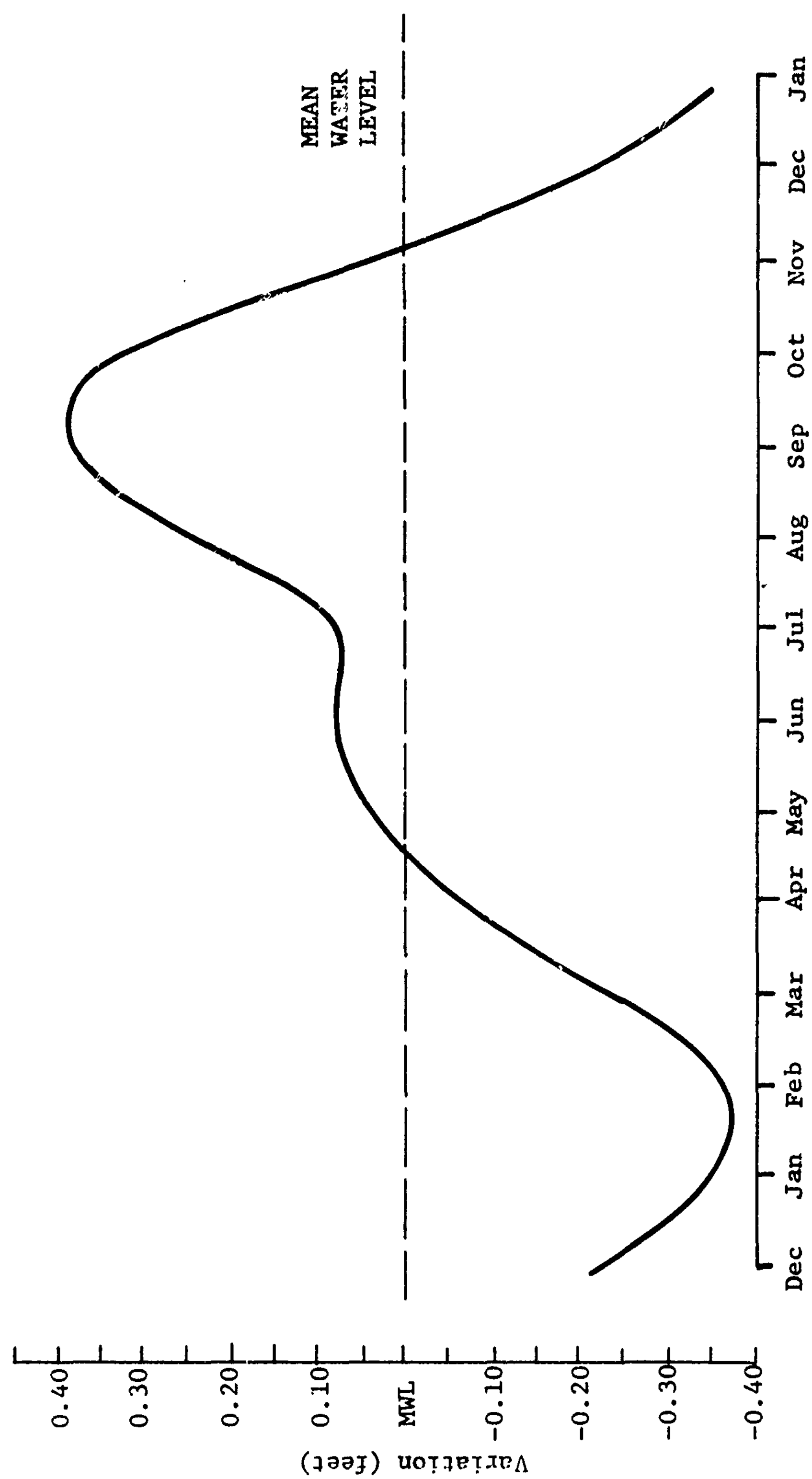


FIGURE 22. ANNUAL VARIATION IN SEA LEVEL FOR NORTHWEST FLORIDA

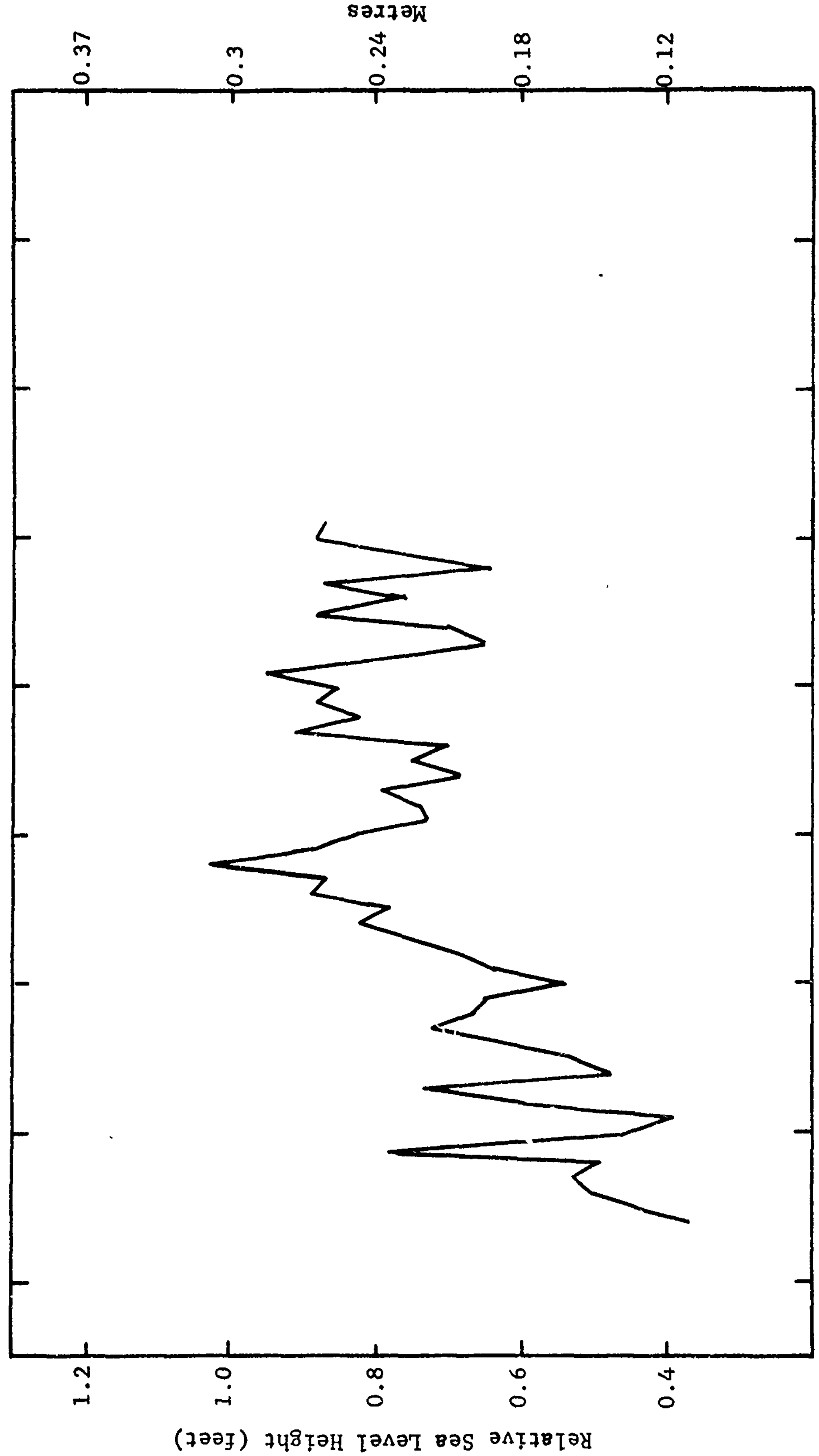


FIGURE 23. YEARLY SEA LEVEL CHANGES AT PENSACOLA

sub-tidal oscillations are generally less than 30 minutes; amplitudes seldom exceed 0.2 feet (0.06 m). Local tide predictions are thus very unreliable during windy periods.

Finally, brief mention should be made of the internal tides observed in local coastal waters whenever the water becomes stratified. Analysis of a long series of vertical temperature profiles from Stage II has revealed that during spring months, when local surface waters are considerably warmer than the water near the bottom, isotherms in the vicinity of the thermocline move up and down in a manner very similar to the conventional surface tide (Reference 17). As shown in Figures 24 and 25, the water column becomes cooler as the surface tide rises, and becomes warmer as the tide falls. These internal waves not only mimic the phase and period of the local surface tide, they also display proportionate fortnightly variations in amplitude, with isotherms undergoing vertical migrations of up to 25 feet (7.6 m) during tropic tide periods, and decreasing to less than 5 feet (1.5 m) during equatorial tide periods. Stratified waters within St. Andrew Bay are also influenced by tidal forces. The bay's surface water layer is generally lighter than the salt water which flows into the bay on each incoming tide. Heavier salt water thus wedges beneath the surface layer, and makes its way up the bay's various arms along the bottom, thereby raising the upper layer to produce the so-called surface tide. These phenomena will be discussed in greater detail in later sections.

## CURRENTS

Numerous observations of current speed and direction have been made in local coastal waters (References 18 through 20) and within the St. Andrew Bay system (References 21 and 22). Unfortunately, these measurements were not taken from enough locations, depths or times to afford a detailed picture of the local flow regime. However, the major components of the local flow have been identified and can be described in a general manner. Observations from Stage I have revealed that the primary mechanism of surface water transport in local coastal waters is wind-induced currents. Rotary tidal currents have also beeen detected during periods of little or no wind. There does not appear to be any permanent or semi-permanent unidirectional currents operating in the nearby coastal area.

A drift bottle study (Reference 18) conducted in 1960 and 1961 revealed that bottles released from Stage I during late spring and early summer were pushed ashore on local beaches by the prevailing seabreeze, whereas bottles released during fall and winter were transported to distant beaches by the winds associated with extra-tropical frontal systems.

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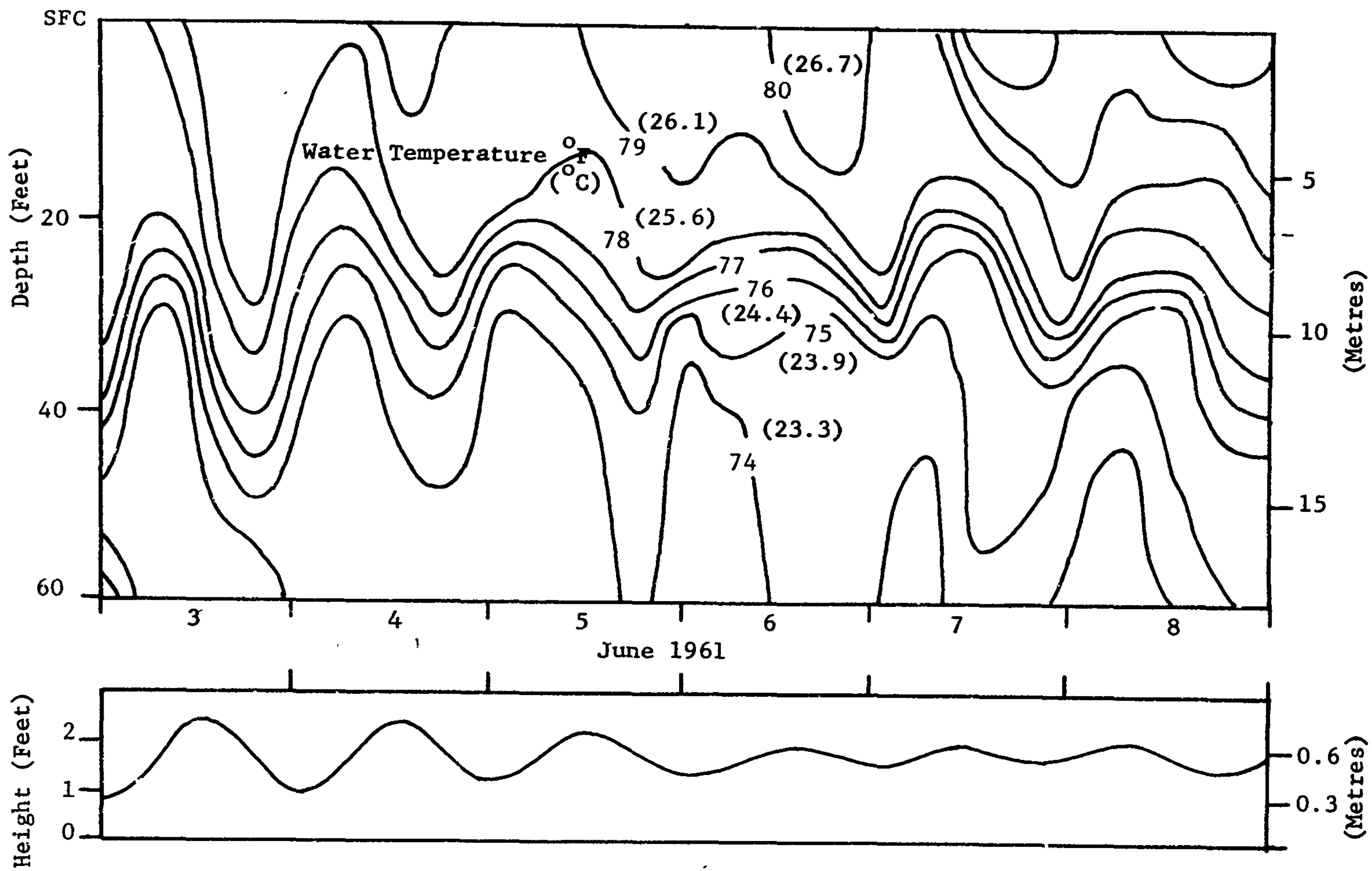


FIGURE 24. WATER COLUMN TEMPERATURE COMPARED WITH DEPTH AND TIDES DURING EQUATORIAL TIDES AT STAGE II

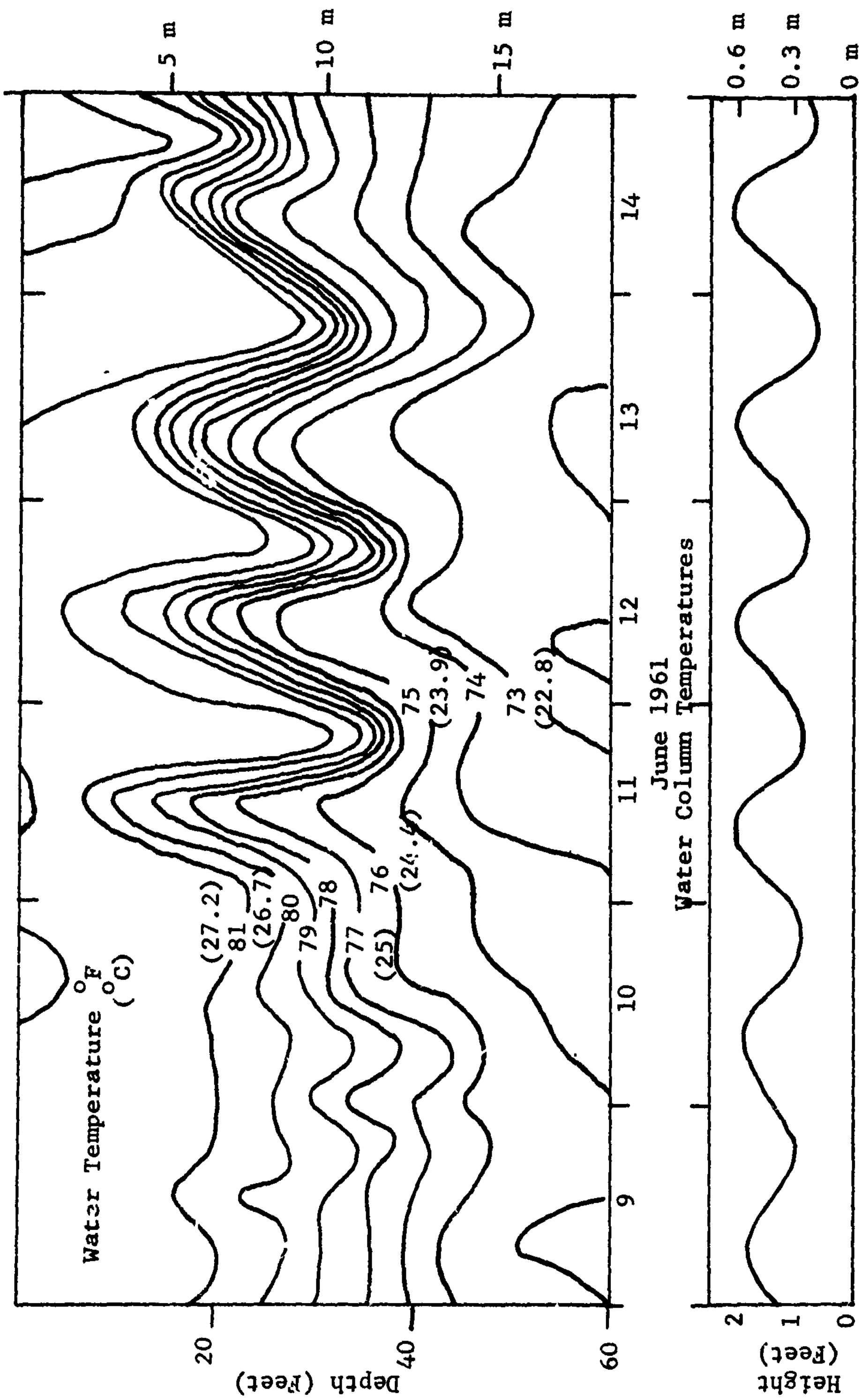


FIGURE 25. WATER COLUMN TEMPERATURE COMPARED WITH DEPTH AND TIDES DURING TROPIC TIDES AT STAGE II

Bottles released *prior* to frontal passages (when southeasterly winds prevail) were usually found in Louisiana or Texas, while those released *after* frontal passages (when northerly winds prevail) were usually found in the Florida Keys or somewhere along the east coast of Florida. Clearly, the wind was the primary mechanism for moving these drift bottles out of local coastal waters to areas where permanent or semi-permanent flows (such as the Eastern Gulf Loop Current or the westerly set off Louisiana) could transport them to their ultimate destinations. Strength of local wind-induced currents varies from 2 to 5 percent of the wind speed, depending on the amount of time the wind has been blowing, as well as on fetch and persistence. A wind of 30 knots could thus generate a surface flow of up to 1.5 knots. Current speeds may increase to as much as 2 knots in local coastal areas during periods of strong and persistent along shore winds. During periods of fair weather, however, current speeds are generally less than 0.5 knots (Reference 1).

Tidal currents in the vicinity of Stage I are of the rotary type, with the direction of flow swinging around the compass as depicted in Figure 26. The rotation is clockwise at a rate of 360 degrees per lunar day. The illustration shows that the surface current sets toward the northwest on or about the time of high water, toward shore during falling tides, toward the southeast on or about the time of low water, and away from shore during rising tides. Strength of this tidal flow varies proportionally with tide range. During tropic tide periods, when local ranges are larger than usual, tidal currents flow at speeds of 0.3 to 0.5 knots. During equatorial tide periods, when local ranges are small, tidal currents are less than 0.1 knot. The tidal excursion associated with these rotary currents is such that a drift bottle released from Stage I at the time of high water (and subjected to only tidal flow) would return very close to the release point 24.8 hours later, after having digressed no more than 3 nautical miles from the Stage. Tidal currents are thus not a very effective transport mechanism in local coastal waters. They can, however, combine with other types of flows to produce currents significantly greater than might usually be expected.

Very little information is available regarding sub-surface tidal currents. But since the surface flow is directed offshore during intervals when the tide is rising, there must be a greater volume of water being transported onshore at sub-surface levels to cause the surface to elevate. Presence of internal tides (mentioned in previous section) provides some evidence of such a counter flow. When local coastal waters are stratified, as during spring and early summer, rising tide is accompanied by an influx of cold water beneath the thermocline. Little is known regarding sub-surface flows during fall and winter when nearby coastal waters are essentially homogeneous.

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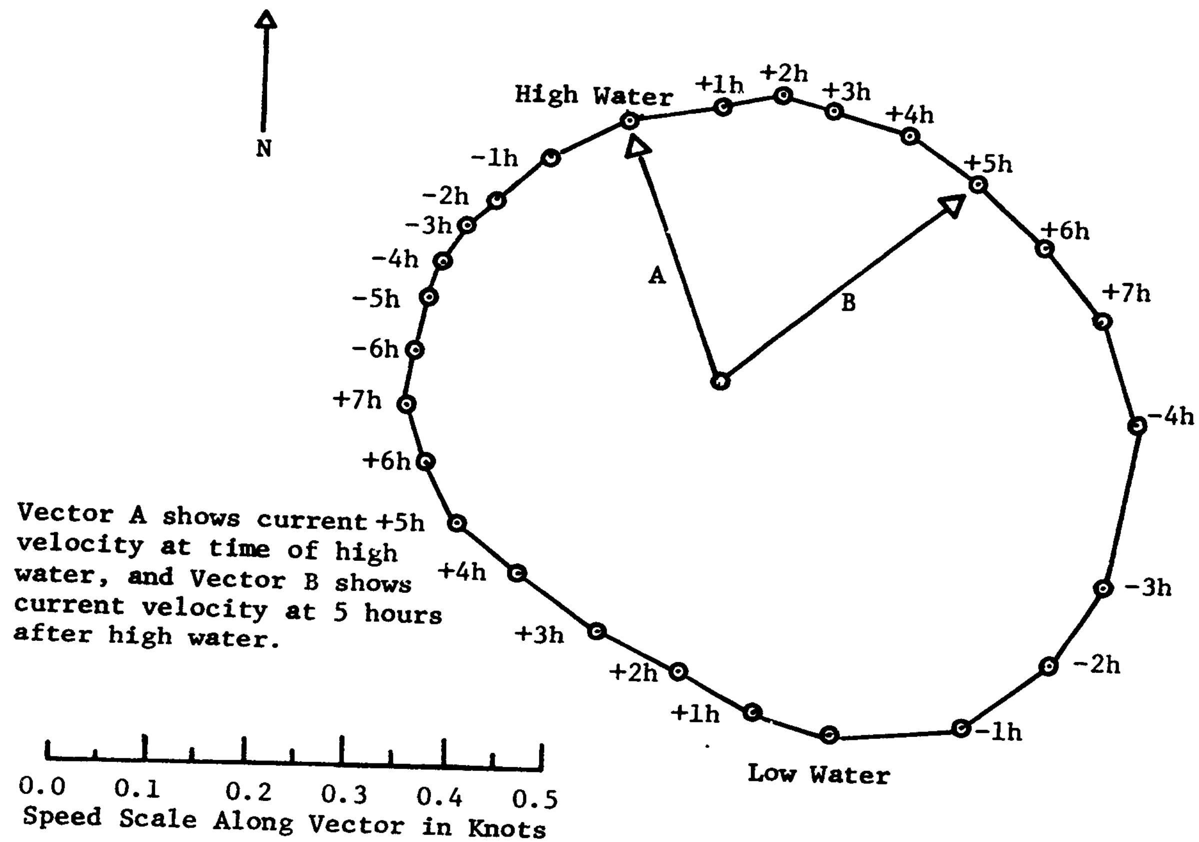


FIGURE 26. ROTARY TIDAL CURRENTS DURING TROPIC TIDE PERIODS AT STAGE I

While permanent or semi-permanent currents (like the Gulf Stream) are not a normal part of the local flow regime, this type of current has been observed further offshore on many occasions, and has been known to occur in the vicinity of Stages I and II for brief periods (Reference 20). Eastward setting currents are quite common along the continental slope south of Panama City, and are usually attributed to the influence of the Eastern Gulf Loop Current (References 23 and 24). Under normal circumstances, this current emanates from the Yucatan Channel, flows northward toward de Soto Canyon, swerves eastward along the West Florida Escarpment, thence southward to eventually exit the gulf through the Straits of Florida. It seldom flows closer than 50 miles (80 km) of Panama City. But variations in the volume of water emanating from the Yucatan Channel, or changing conditions in the central gulf, can alter the normal flow pattern, forcing the Loop to change its course (perhaps to a more northerly latitude), to develop a series of sinuous meanders (in much the same fashion as do rivers, and the Gulf Stream), or to shed vortexes along its perimeter. If a medium to large scale meander or eddy migrated up onto the northwest Florida Shelf, it would generate currents substantially stronger than those normally encountered there. Currents of up to 2 knots have been observed in the vicinity of Stages I and II on such occasions (Reference 20). Fortunately, a current of this type is only temporary, lasting for several days, never longer than a week. Most likely season for such perturbations is springtime.

Discussions with other investigators studying this part of the Gulf of Mexico have revealed a growing body of new and as yet unpublished data showing that effluent from the Mississippi River is not always diverted westward toward Texas, but occasionally makes its way to the east where it merges with the Eastern Gulf Loop Current. NCSC oceanographers observed this phenomenon while making a series of measurements from a moored vessel 54 miles (87 km) southwest of Panama City in August of 1974 (Reference 19). For a period of several days, they observed occasional logs, branches, and clumps of water hyacinth drifting past their vessel. Current was setting toward the east-southeast at a speed of approximately 1 knot. Surface water was green in color rather than its customary blue, and the salinity was only 26 parts per thousand, a full 10 parts per thousand lower than normal for this part of the gulf. Water closer to Panama City retained its characteristic oceanic properties during this period, but might not have done so if strong southerly winds had arisen to deflect the brackish effluent toward local beaches.

As might be expected, the flow regime within St. Andrew Bay differs considerably from that in the nearby Gulf of Mexico. Entrance channels are swept by relatively strong tidal currents. Within the main ship channel, the current floods for approximately 15 hours and ebbs for 10

hours, peak flows varying proportionally with daily tide range. During periods of tropic tides, flood currents reach speeds of 1 to 1.5 knots, and ebb currents reach as high as 2 knots at the "jetties" (Figure 27). During periods of equatorial tides, neither flood nor ebb can be expected to exceed 0.5 knot (Figure 28). Figure 27 reveals that flood cycle consists of two separate peaks, whereas the ebb cycle exhibits only one. Duration of slack following each flood cycle is significantly longer than the duration of slack following ebb cycles. Surface currents as great as 3 knots can be expected within the main entrance channel if an outgoing tropic tide is accompanied by strong northerly winds.

An associated phenomenon of considerable interest is the distinctive "tide line" (Reference 25) which separates the brackish water of St. Andrew Bay (normally greenish brown in color) from the salty water of the Gulf of Mexico (normally blue-green in color). Incoming tide causes this line to retreat about one to two miles back up into the bay, from which point the heavy salt water plunges beneath the line and wedges upchannel along the bay's bottom. But when the flood cycle ceases, the tide line begins to move seaward. It passes through the main entrance channel about 1.5 hours after high water, and begins to spread out across the surface of the Gulf of Mexico as a thin brown layer. In the absence of wind, it makes its way as much as 7 miles out to sea; southeasterly winds divert it toward Panama City Beach, while northwesterly winds divert it toward the shores of Shell Island. Heavy seas cause it to mix with underlying salt water, thereby forming a coastal water mass of intermediate properties. A new tide line then forms within the bay entrance just as soon as the next flood cycle commences.

Current speeds within the bay are generally less than 0.5 knots, except near constrictions and within certain bends, where surface speeds may be briefly higher during some periods. Surface flows of up to 1.5 knots have been observed in the big bend just east of NCSC (Reference 22). Flows of this magnitude can be expected only when northerly winds are helping to empty the bay during the ebb phase of tropic tide cycles. North Bay is the only arm of the bay system into which significant volumes of fresh water feed. A dam was constructed across the uppermost part of North Bay to form a reservoir to store fresh water from Econfina Creek. Mean annual runoff from this spring-fed creek is approximately 500 cubic feet per second. Surplus pours over the top of dam and makes it way down the northern arm of bay at speeds of 0.1 to 0.2 knots.

## WATER COLUMN CHARACTERISTICS

NCSC oceanographers have made numerous observations regarding the temperature, salinity, density, sound velocity, color and clarity of

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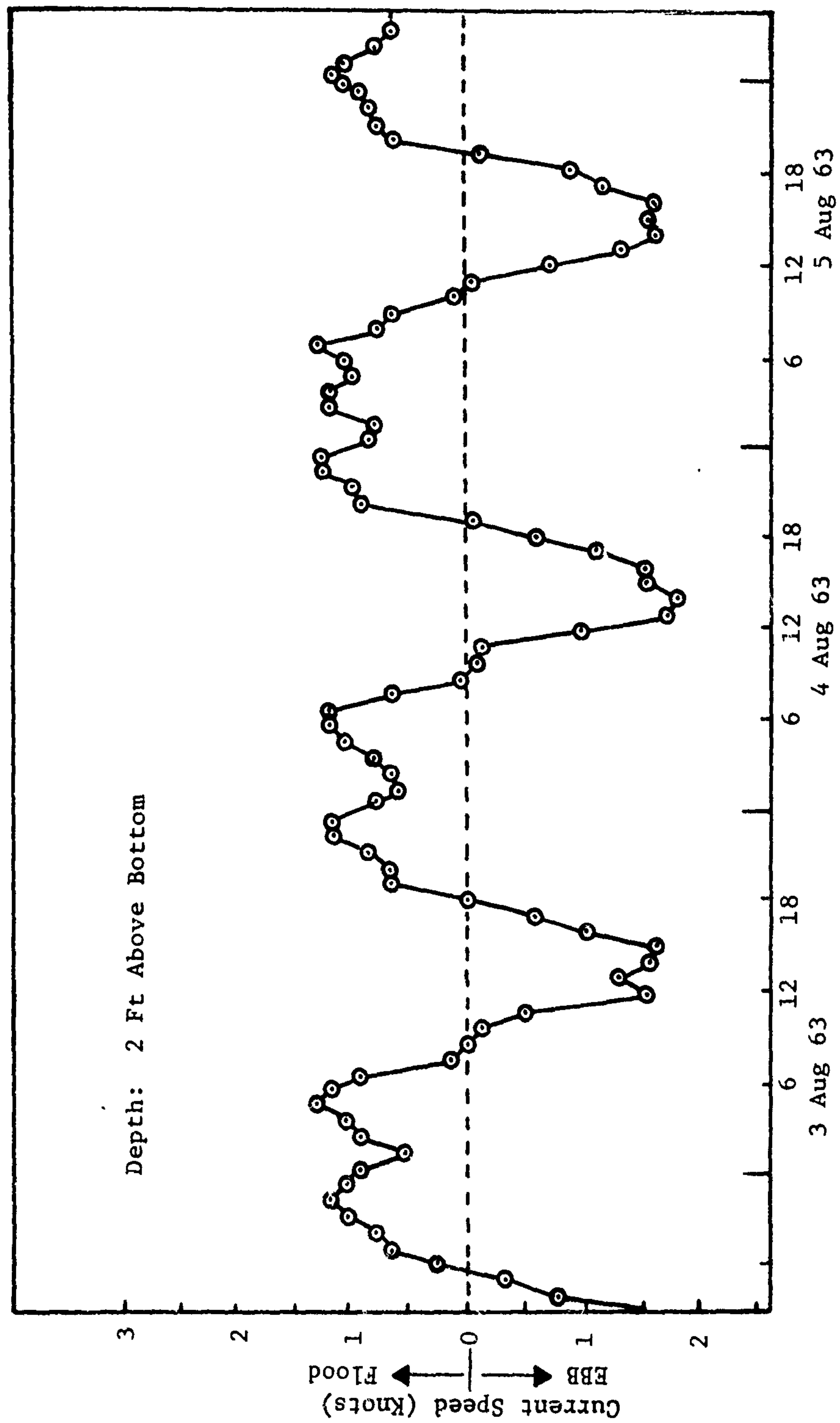


FIGURE 27. TIDAL CURRENTS AT ST. ANDREW BAY ENTRANCE CHANNEL DURING TROPIC TIDE INTERVAL

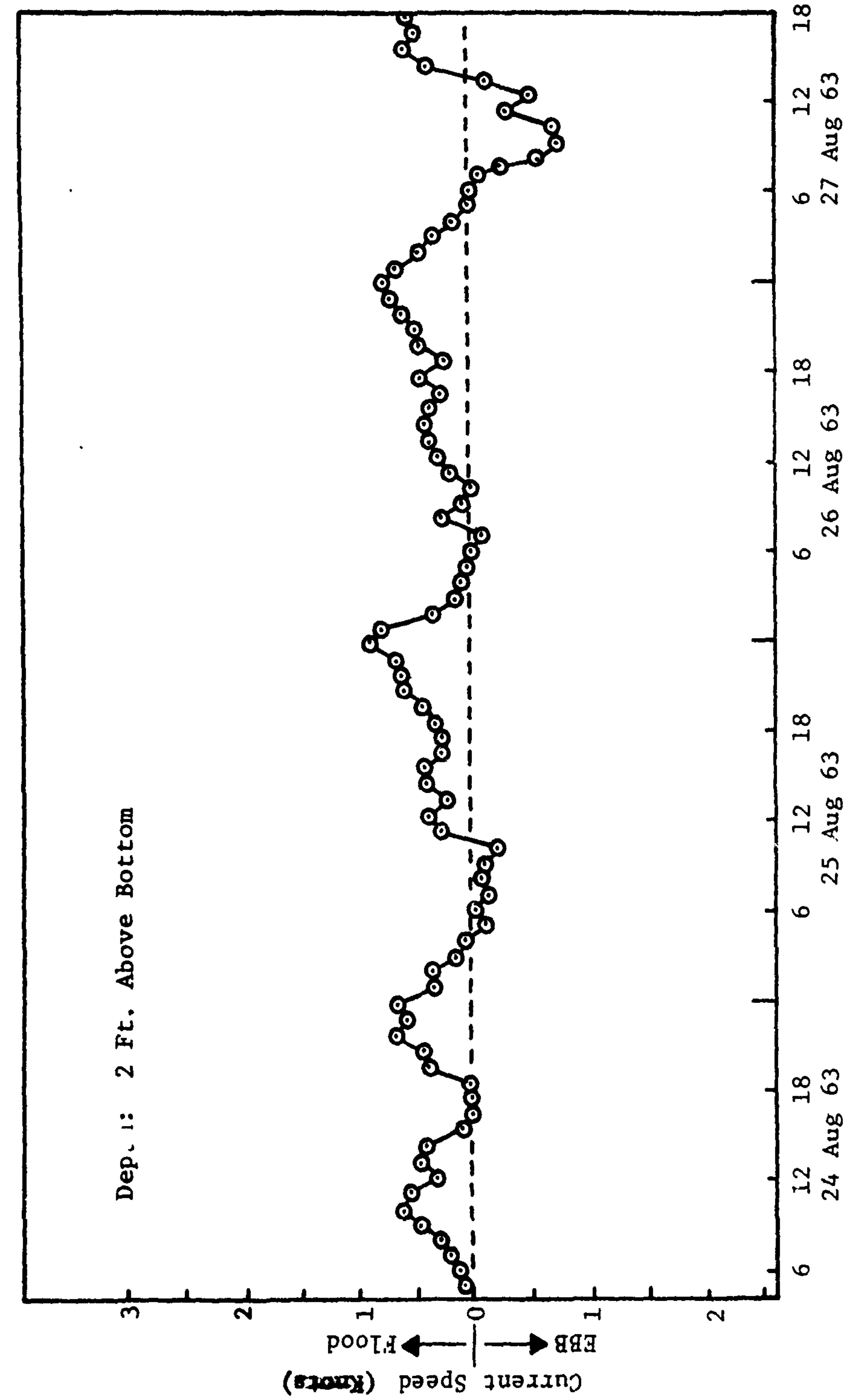


FIGURE 28. TIDAL CURRENTS AT ST. ANDREW BAY ENTRANCE CHANNEL DURING EQUATORIAL TIDE INTERVAL

local waters, and have acquired a general understanding of the manners in which these parameters vary as functions of place, depth, tide, storm and season. Much of the observed variability is associated with the basic differences which exist between local gulf and bay waters. While the nearby gulf is characteristically warm, salty, dense, blue-green in color, and relatively free of suspended materials, the waters of St. Andrew Bay are usually brackish, light, greenish brown in color, and contain various materials in both suspension and solution. It is thus relatively easy for even an untrained observer to detect the so-called "tide line" which marks the point of contact of these two bodies of water. Difference in density contributes greatly to local stratification, especially within the bay, where two distinctive layers are present practically all year. Seasonal heating and cooling also produce gradients, especially in the gulf. Specific examples of horizontal and vertical gradients observed in local waters are presented below. Separate sections are provided for information relating to water temperature, salinity, density, sound velocity, and clarity. These sections contain brief descriptions of seasonal trends and the temporal effects of storms.

## WATER TEMPERATURE

The annual surface water temperature cycle at Stage II is depicted in Figure 29. Monthly mean values are indicated by the heavy dashed curve, which shows that the local sea surface cools to approximately 57°F (14°C) in January, and warms up to about 86°F (30°C) in August. The mean rate of fall during autumn is considerably greater than the mean rate of rise during spring. Mean daily temperature curves are also plotted in Figure 29. These curves reveal the presence of numerous short-period fluctuations, with considerable departure from monthly mean values. These fluctuations are especially pronounced during winter and spring, and have been linked with weather changes accompanying the passage of extratropical high and low pressure systems. Surface water temperatures decrease during the cool days which follow the passage of cold fronts, and increase during the warm days which precede the passage of the next front. But the observed fluctuations do not result from local heating and cooling alone, for wind-induced currents are also responsible. The southerly winds which typically precede the passages of cold front bring warm water in from further offshore, while northerly winds which follow fronts move cold coastal waters seaward. Interestingly, it is only during winter and spring that offshore surface waters are substantially warmer than local coastal waters (Reference 26). Surface temperature fluctuations at Stage II are thus greater during these seasons than at other times of the year.

Typical vertical temperature profiles for the four seasons are presented in Figure 30. Structure is characteristically isothermal from summer through fall and winter, with temperature decreasing at all

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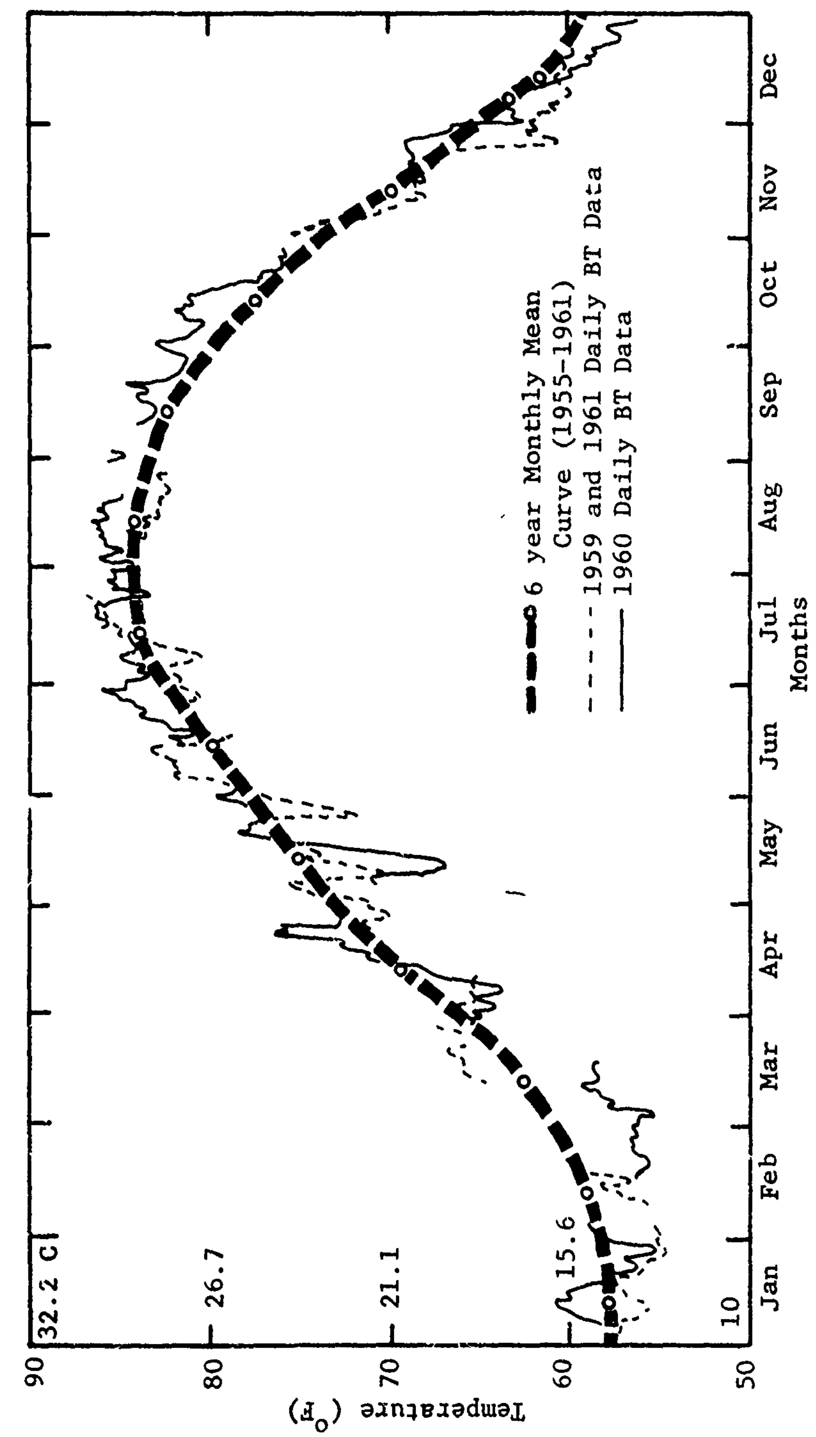


FIGURE 29. ANNUAL SURFACE WATER TEMPERATURE CYCLE AT STAGE II

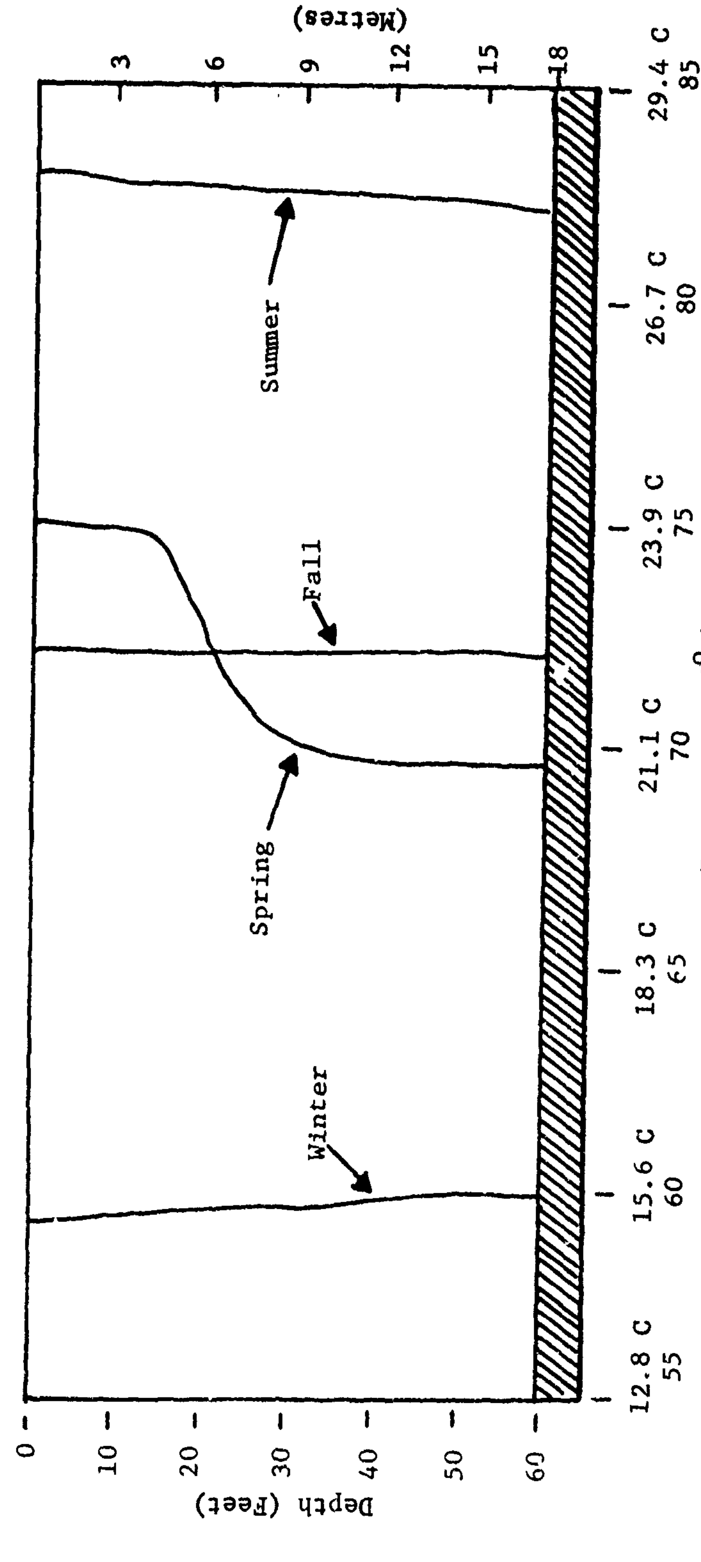


FIGURE 30. TYPICAL SEASONAL BATHYTHERMOGRAPH RECORDS FROM STAGE II

depths as cold fronts pass to mix the water column and drain heat from it. Warming of surface waters in the spring causes a thermocline to develop near mid-depth. A plot of the mean surface-to-bottom temperature difference at Stage II is provided in Figure 31. May and June are clearly the months of greatest thermocline development. Actual surface-to-bottom differences of up to 15°F (8.3°C) have been encountered in the vicinity of Stage II on some spring days (Reference 17).

The internal waves which frequent local coastal waters during the spring and early summer are of great interest to NCSC oceanographers. Reference has already been made to the tidal frequency internal waves observed at Stage II and Stage I during these seasons. As shown in Figures 24 and 25, these internal tides cause the local thermocline to rise and fall in much the same manner as does the classic surface tide. Isotherms in the central portion of thermocline undergo vertical displacements which are proportional to, but considerably larger than, the corresponding surface tide range. Displacements of up to 25 feet (7.6 m) can be expected during periods of tropic tides, while during equatorial tides, displacements are generally less than 10 feet. Mean daily temperature change at a depth of 30 feet (9 m) is approximately 4°F (2.2°C); maximum recorded change is 6°F (3.3°C). Internal waves of higher frequency have also been observed in local coastal waters (Reference 4). But the characteristically small amplitudes and low speeds of these high frequency waves makes them rather difficult to detect in the presence of turbulence.

The springtime thermocline disappears temporarily whenever storms bring heavy seas to the area. Nearshore waters then become well mixed, but it only takes a few tidal cycles to re-establish a thermocline after seas have calmed. As the season progresses, the thermocline gradually retreats to deeper water. While it is seldom observed at Stage II after July, portions of it can still be found near the bottom at Stage I during August and September. Details of the thermal structure across the shelf during August are presented in Figure 32 (Reference 27), where it can be seen that the thermocline is essentially horizontal, and the majority of isotherms intersect the bottom seaward of Stage I. But rapid cooling and mixing during fall cause the structure to change dramatically. By December the thermocline has disappeared from inner shelf waters and has been replaced by a horizontal gradient (Figure 33). Water in the vicinity of each stage is then essentially vertically isothermal with water near the beach cooler than that offshore. Horizontal gradients as steep as 1°F (0.6°C) per nautical mile have been observed between Stage I and shore during January and February. The thermocline is re-established by surface heating during early spring.

The shallow waters of St. Andrew Bay tend to (a) warm more rapidly than local gulf waters during spring, (b) remain warmer through the summer, (c) cool more rapidly during the fall, and (d) remain cooler through

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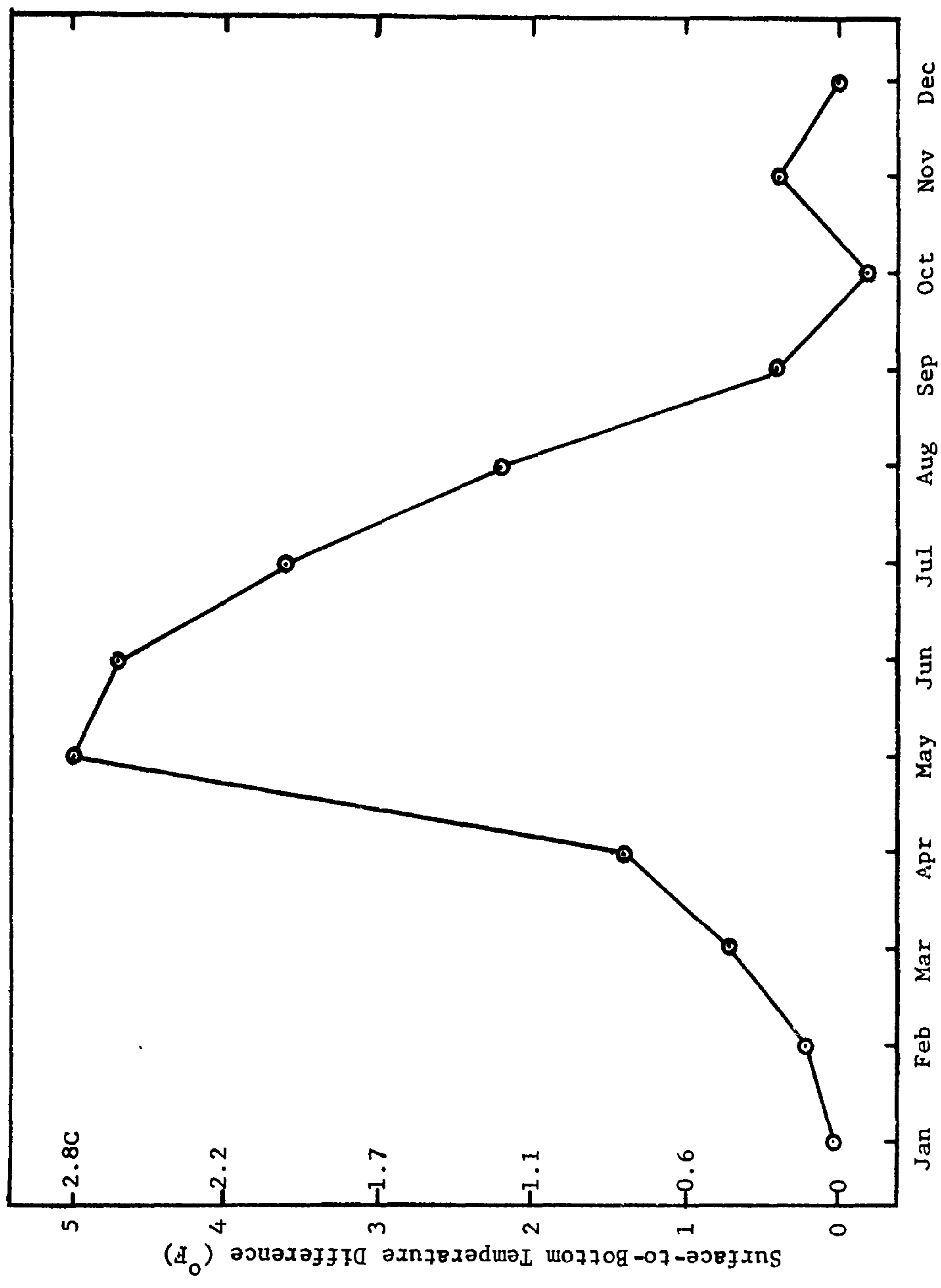


FIGURE 31. MEAN SURFACE-TO-BOTTOM TEMPERATURE DIFFERENCE AT STAGE II

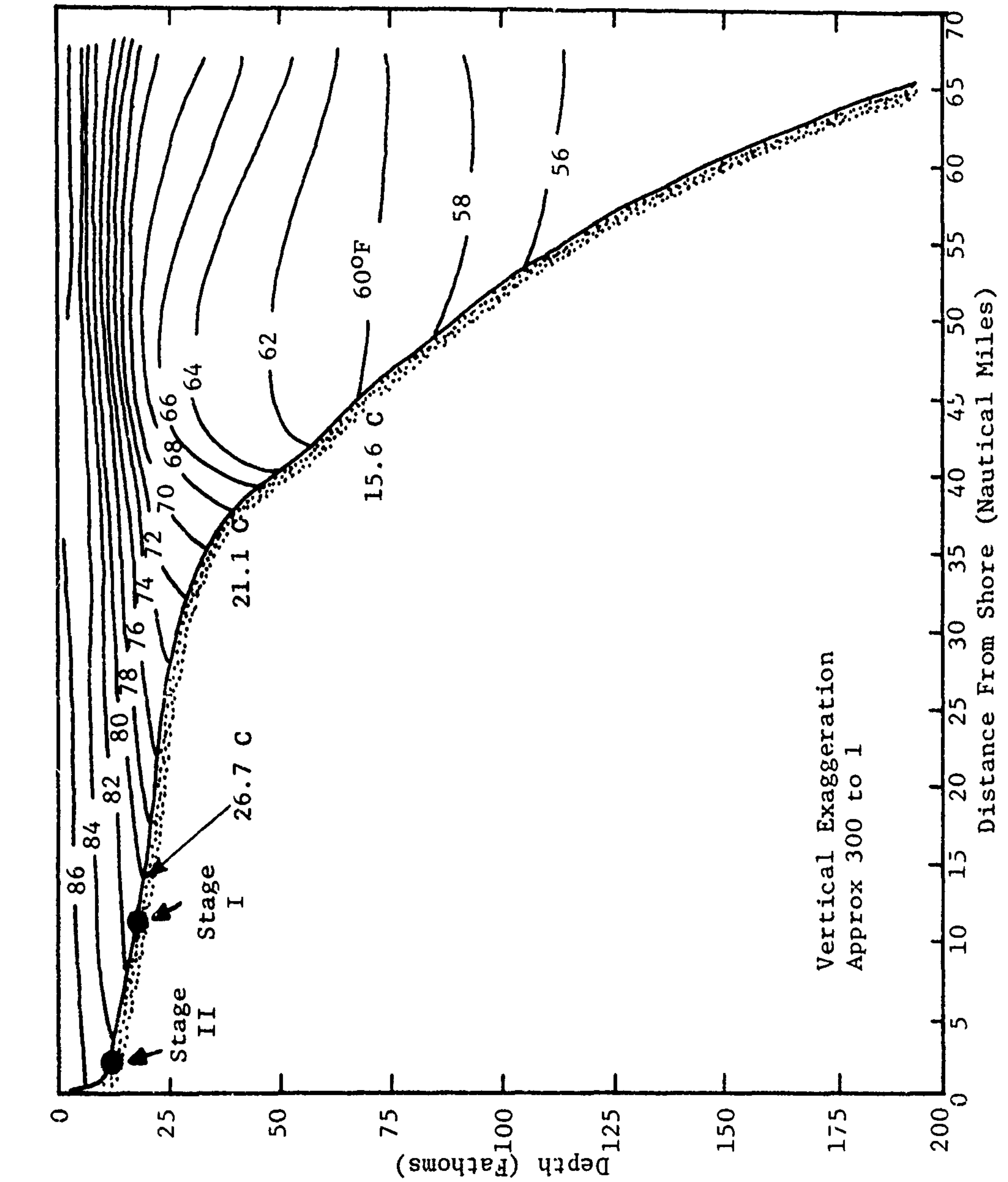


FIGURE 32. THERMAL STRUCTURE OVER SHELF AND SLOPE DURING 7 AUGUST 1963

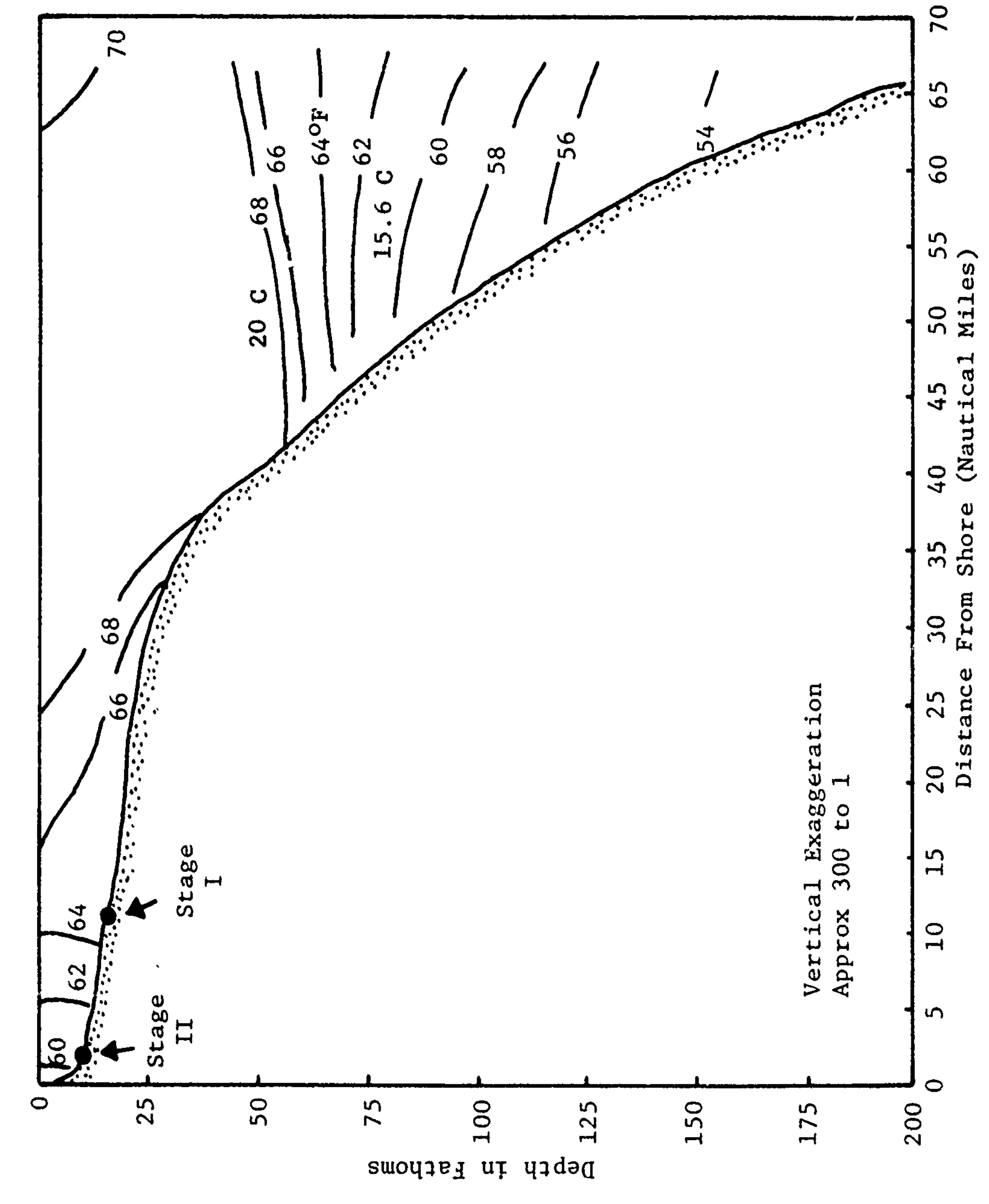


FIGURE 33. THERMAL STRUCTURE OVER SHELF AND SLOPE DURING 11 DECEMBER 1963

the winter. Surface water temperatures as high as 89°F (31.7°C have been observed within the bay on hot summer days. During cold spells in January and February, surface temperatures may dip to as low as 45°F (7°C) in the broad central portions of the bay. Thin sheets of ice have been known to form on the surface of local bayous during severe cold spells. The gulf-like waters found at subsurface levels in the bay do not undergo such drastic temperature changes as do surface waters (Reference 22). Bottom temperatures range from 1 to 7°F (0.6 to 3.9°C) cooler than surface temperatures during spring and summer, and up to 5°F (2.8°C) warmer during winter. Plots of typical surface and bottom temperatures at selected locations in the western arm of St. Andrew Bay during the month of December are provided in Figure 34. Curves in this figure show that water near the mouth of bay is essentially isothermal, and is considerably warmer than the isothermal water in shallow upper reaches of bay. But substantial positive vertical thermal gradients are present within the central portion of bay. Since warm water is lighter than cold water, it could normally be expected that such a gradient would overturn; but the high salt content of the warm subsurface layer provides the additional weight needed to maintain stability through the winter months. Positive gradients of comparable magnitude are not likely to be found in local gulf waters during any season.

## SALINITY

### Gulf Area

Salt content of nearby coastal waters is characteristically high throughout the year, with salinity values often exceeding 34 parts per thousand at Stage II (inshore platform) and 35 parts per thousand at Stage I (offshore platform) (References 1 and 28). Slightly higher values can usually be expected further offshore. Weak vertical gradients are also present during most seasons, with subsurface waters ranging from 1 to 1.5 parts per thousand saltier than surface waters. Some seasonal variability has been noted, but changes of larger magnitude can be expected whenever unusual weather patterns develop. Local salinities tend to increase during periods of drought or persistent onshore winds, and tend to decrease during periods of heavy rainfall or offshore winds. As might be expected, variability is greater at Stage II than at Stage I. Values as low as 31 parts per thousand have been recorded at the surface at Stage II following the passage of a "tide line." But as this brackish effluent from St. Andrew Bay spreads out across the surface of the nearby gulf, it is eventually attacked by wind waves, which mix it with underlying ocean water to produce a surface water mass of intermediate salinity. Values as high as 38 parts per thousand were recorded in the vicinity of Stage I during the extremely dry spring of 1977. Salinities as low as 25 parts per thousand have been observed further offshore near the edge of the continental shelf, and constitute evidence that

(Text Continued on Page 54)

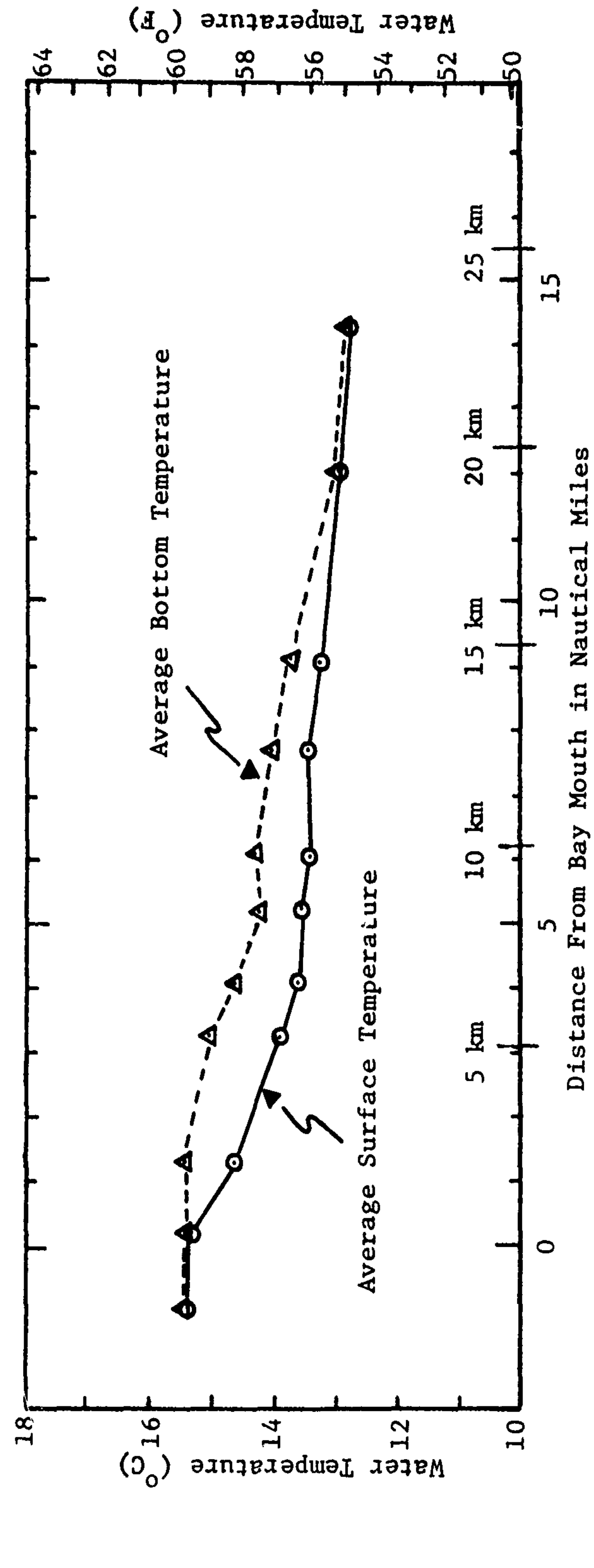


FIGURE 34. WATER TEMPERATURES IN ST. ANDREW BAY DURING DECEMBER

Mississippi River effluent may not always be diverted toward Texas (Reference 19). Such occurrences are, however, comparatively rare. Nearshore gulf waters must be regarded as a high salinity environment, with few significant horizontal or vertical salt gradients present during any season.

St. Andrew Bay

Salinity gradients within St. Andrew Bay are far steeper than those normally encountered in the nearby gulf. Plots of typical surface and bottom salinities at selected locations in the western arm of the bay during the month of December are provided in Figure 35. Curves in this figure show that water near the mouth of the bay is essentially isohaline, and is considerably saltier than the water found in shallow upper reaches of bay. But within the central and upper reaches of the bay, surface salinity values average about 2 parts per thousand lower than bottom values. Even greater differences are noted during some stages in the tide. During incoming tides, the interface between brackish bay water and salty gulf water ascends toward the surface; while during outgoing tides, the interface descends. Periods of heavy rainfall cause the halocline to intensify, while extended droughts cause it to dissipate. Sudden wind shifts also have a dramatic effect on the bay's salinity structure. Figure 36 is an isohalinic profile at a site 1 mile east of NCSC and shows the changes which took place during the passage of an atmospheric cold front. Post-frontal northerly winds caused the bay's surface layer to move seaward, thereby lowering surface salinities from 26 to 19 parts per thousand, and temporarily causing the halocline to intensify. While salinity gradients within St. Andrew Bay are not normally as steep as those depicted in Figure 36, gradients of lesser magnitude can be expected on practically any day throughout the year.

DENSITY

Sea water density is a function of temperature, salinity, and pressure (depth). An increase in salinity or pressure will produce a corresponding increase in density, while an increase in local water temperature has the opposite effect (local water temperatures are almost always greater than 39.2°F (4°C), the so-called temperature of maximum density of fresh water). Density of local coastal waters must therefore be lower during summer than winter. Typical annual density cycle at Stage II is depicted in Figure 37. Values generally hover between 1.021 and 1.026 grams per cubic centimeter (Reference 4). Slightly higher values can usually be expected at depths as shown in Figure 38. Steepest vertical gradients are encountered during spring and early summer, when subsurface waters are cooler and saltier than surface waters. Internal wave activity is usually

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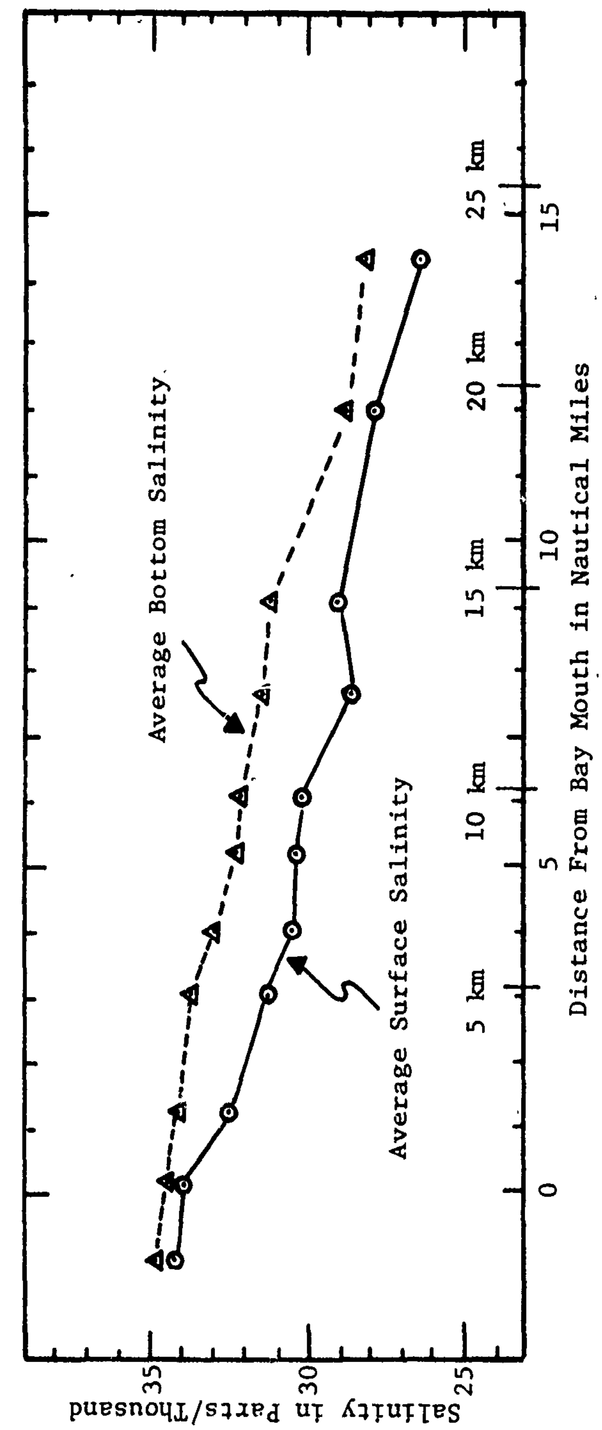


FIGURE 35. SALINITY VALUES IN ST. ANDREW BAY DURING DECEMBER

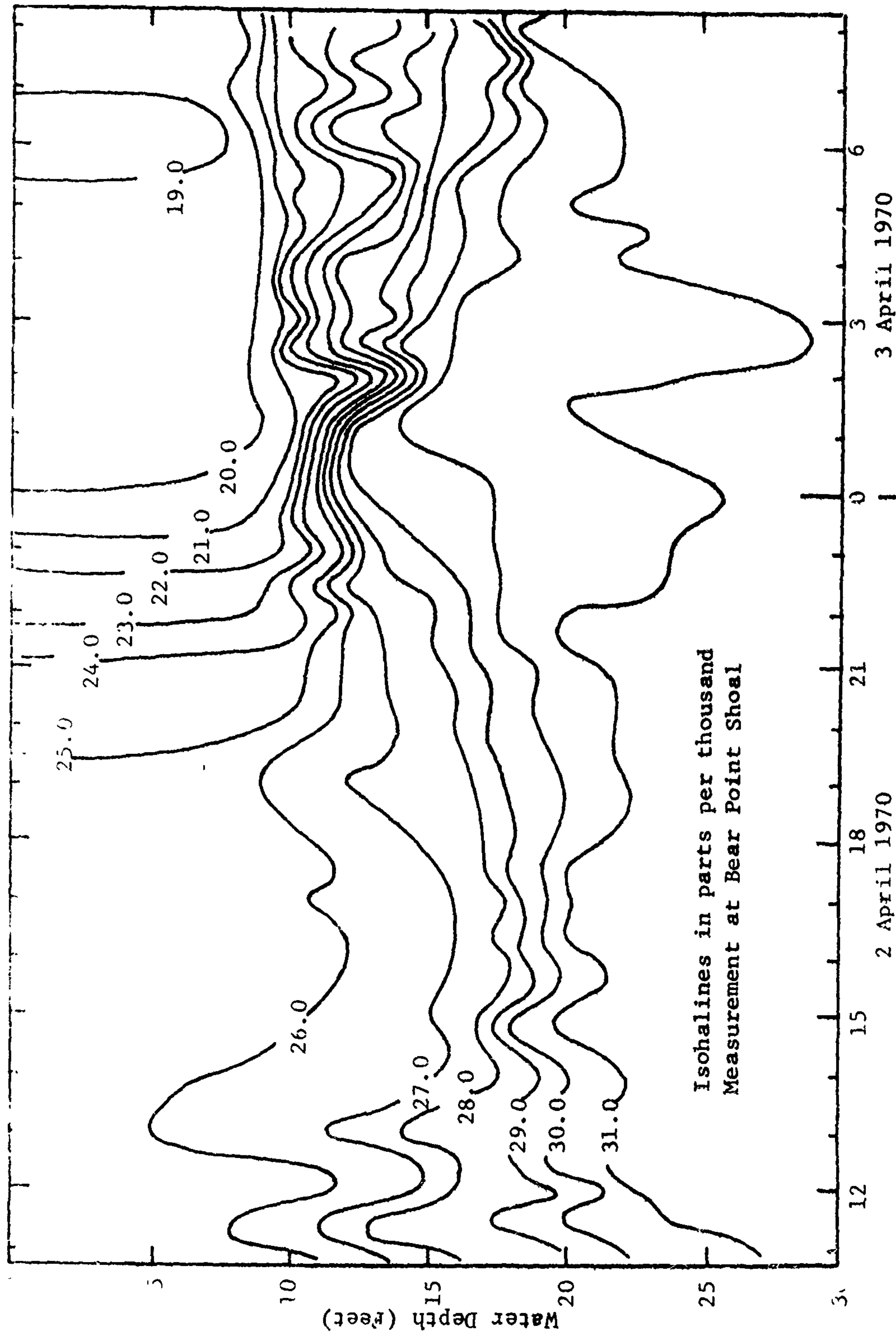


FIGURE 36. SALINITY STRUCTURE IN ST. ANDREW BAY DURING COLD FRONT PASSAGE

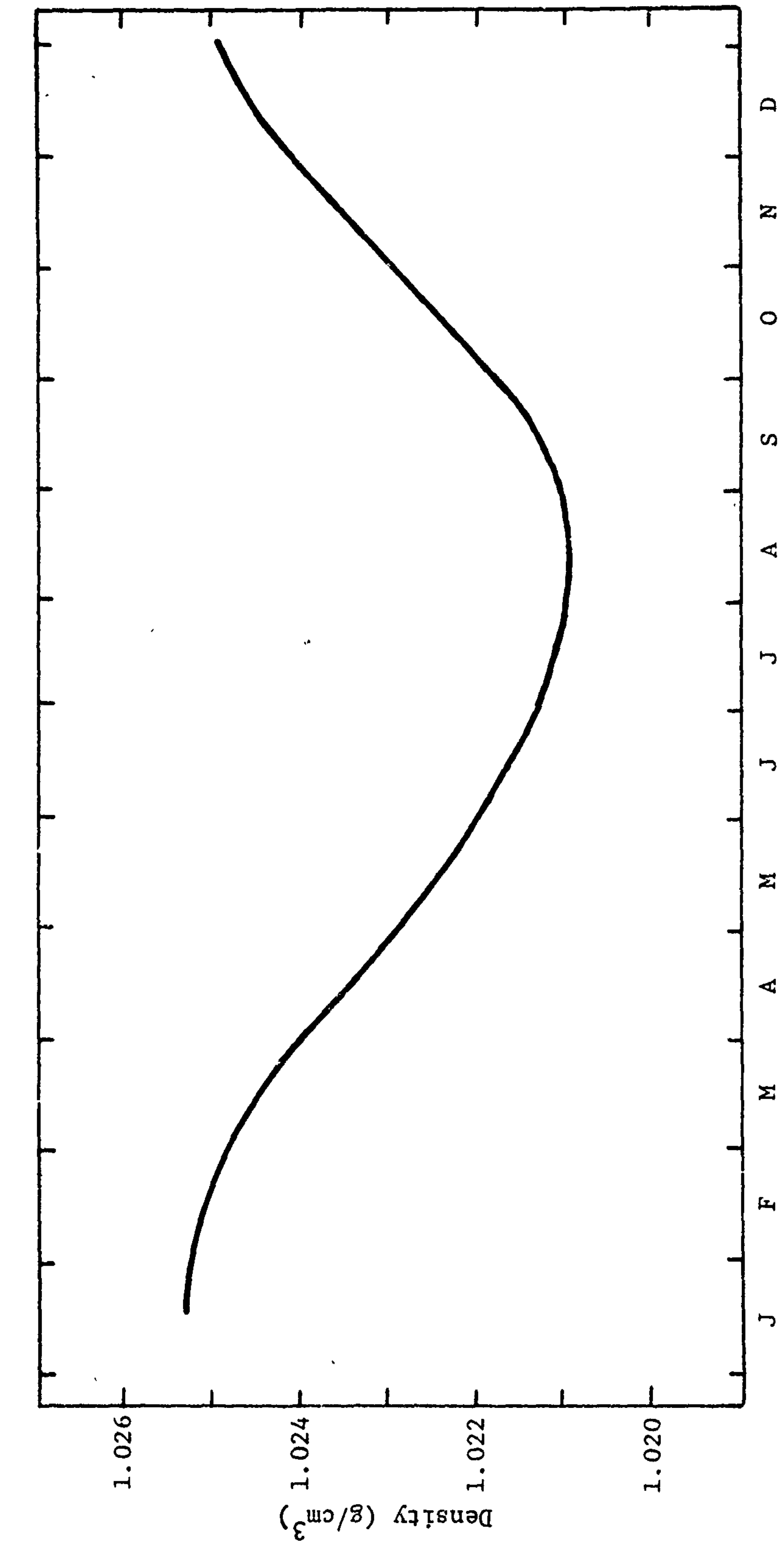


FIGURE 37. ANNUAL SEA SURFACE DENSITY CURVE AT STAGE II

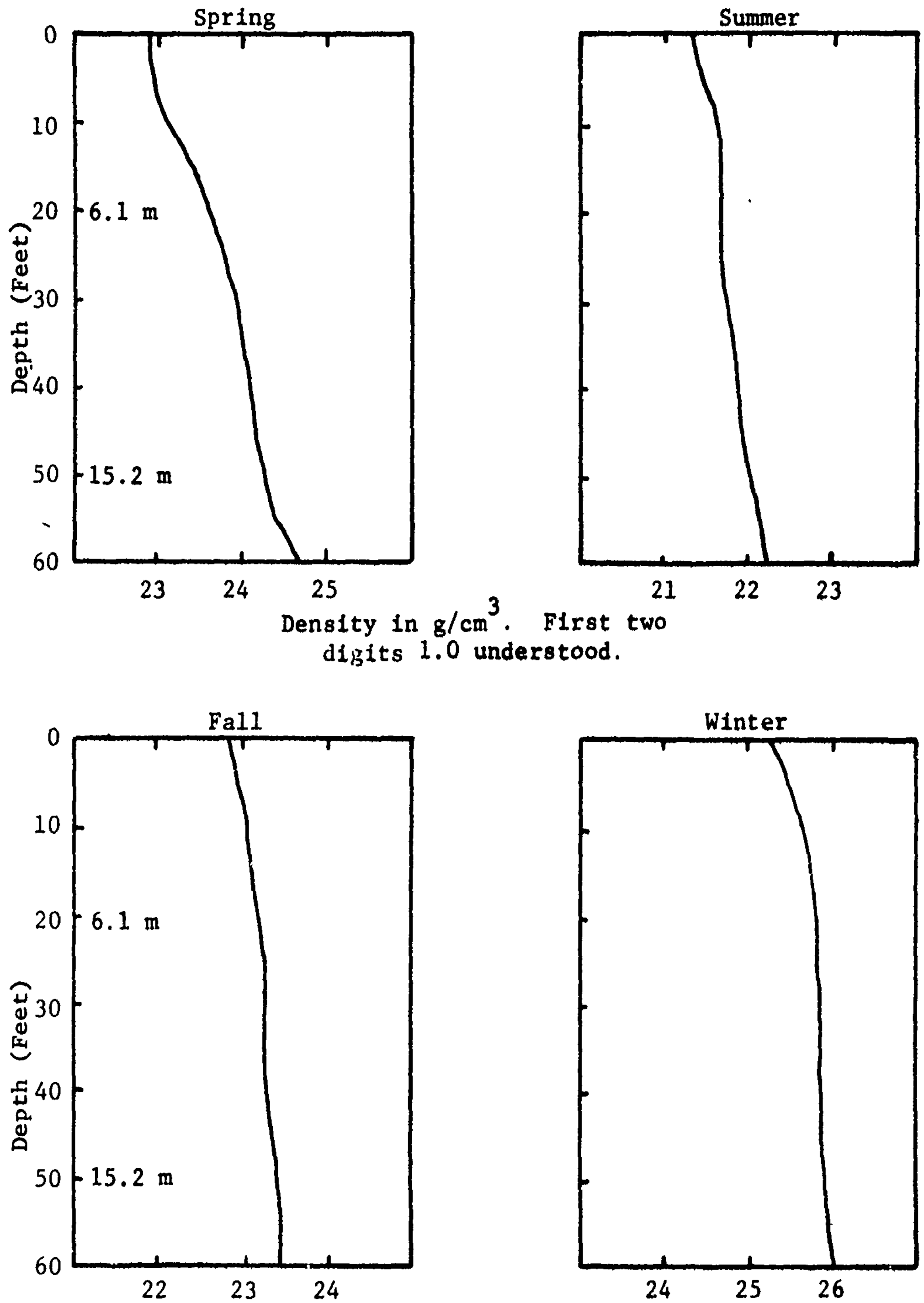


FIGURE 38. TYPICAL SEASONAL DENSITY PROFILES AT STAGE II

more pronounced during this time of year than during other seasons. Horizontal density gradients are also present in the nearby gulf, but are usually of small magnitude. Offshore waters are generally more saline than inshore waters, and should thus be slightly denser; but during winter months, inshore waters become much cooler than those offshore, and the horizontal gradient reverses. As might be expected, heavy rains tend to dilute local surface waters and cause densities to decrease, while the opposite is true during droughts and periods when evaporation is greater than normal. Densities as low as 1.016 grams per cubic centimeter have been reported from Stage II following the passage of bay effluent on outgoing tropic tides.

The density structure within St. Andrew Bay is even more diverse than that in the nearby gulf. Vertical and horizontal gradients of appreciable magnitude are present during all seasons. Values range from a minima of approximately 1.010 grams per cubic centimeter in the bay's upper reaches during summer, to a maxima of approximately 1.025 grams per cubic centimeter near the bay's mouth during winter. Densities remain fairly high throughout the year in the bay's salty bottom layer, but considerable variations are encountered in the brackish surface layer. As a general rule, bay surface densities tend to increase during rising tides, cold clear nights, and periods of extended drought or southerly winds; conversely they tend to decrease during falling tides, hot afternoons, periods of heavy rainfall, or northerly winds. Figure 39 shows the steep vertical gradient which developed at a site 1 mile east of NCSC during the passage of an atmospheric cold front. Density of surface layer decreased to less than 1.013 grams per cubic centimeter as the post-frontal northerly winds swept over the bay, causing vertical gradient to steepen considerably. Very severe storms, such as hurricanes, have been known to completely mix the waters of St. Andrew Bay, but a positive density structure is reestablished by the next tropic tide interval.

## SOUND VELOCITY

The speed with which acoustic energy is transmitted through an aqueous medium is a function of water temperature, salinity and depth (pressure). An increase in any of these three parameters produces a corresponding increase in sound velocity, and vice-versa. Increase due to depth amounts to only 1.7 metres per second per 100 metres of depth, and can thus be ignored in the shallow waters of St. Andrew Bay and the nearby gulf coastal area. But the effects of temperature and salinity cannot be ignored. As shown in Figure 40, sound velocities vary about 40 metres per second during the course of a year in the vicinity of Stage II. The

(Text Continued on Page 62)

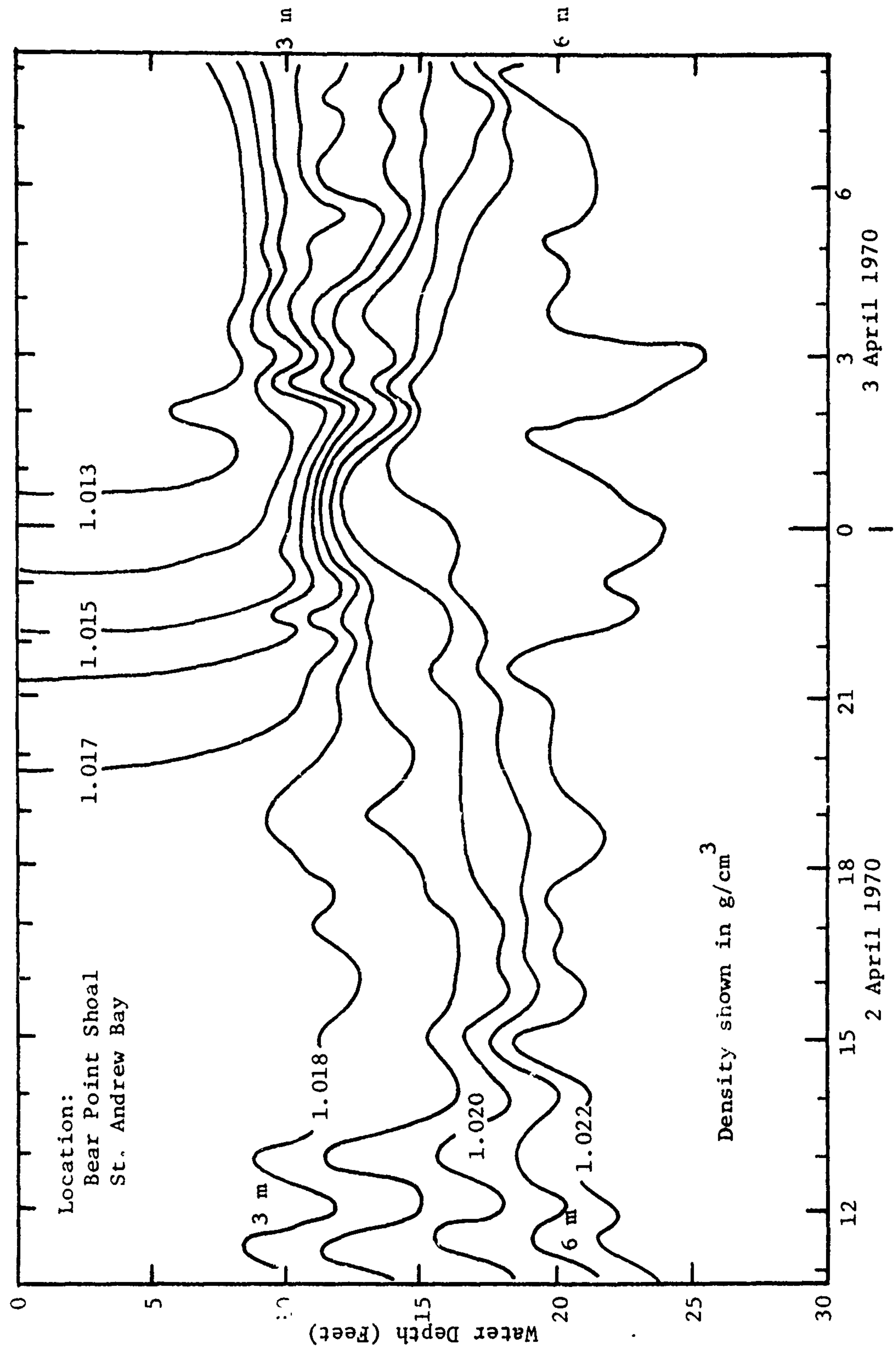


FIGURE 39. DENSITY STRUCTURE DURING COLD FRONT PASSAGE

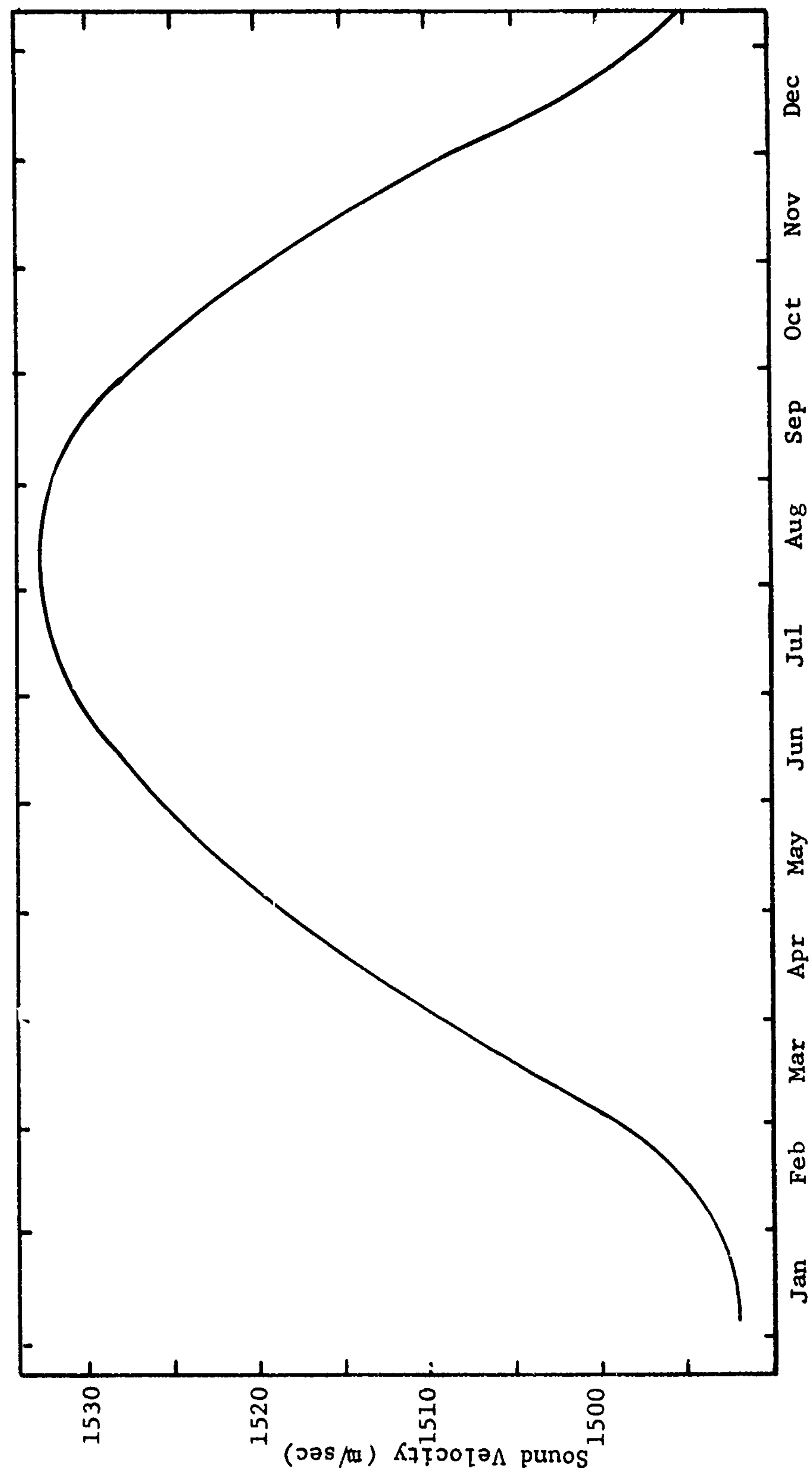


FIGURE 40. ANNUAL SEA SURFACE SOUND VELOCITY CURVE AT STAGE II

bulk of this change is caused by annual temperature variations. Sound velocity values in the neighborhood of 1500 metres per second can be expected during winter months when local waters are cool (Reference 1), and values of approximately 1540 metres per second can be expected during summer months when local waters are warm. Appreciable horizontal sound velocity gradients are only present in the gulf during winter months when offshore waters are warmer than those nearshore. Sound velocities in the warmer water may be up to 20 metres per second faster than in nearshore area. As in the case of salinity and temperature, coastal sound velocities can be expected to increase during periods of extended drought or onshore winds, and to decrease during periods of heavy rain or offshore winds.

Typical vertical sound velocity profiles at Stage II during the four major seasons are presented in Figure 41. Steepest vertical gradients are generally encountered during late spring and early summer, when the surface layer becomes significantly warmer than the bottom layer. Sound velocities are then higher near the surface than at depth, and horizontally projected acoustic beams are refracted downward. A negative gradient of 11 metres per second is depicted in Figure 42. This cross-sectional view of the nearshore sound velocity structure was obtained during a period of rising tide, when cool subsurface water was being directed onshore and was causing the thermocline to be displaced upward near the beach. The steep negative sound velocity gradients of late spring and early summer give way to weak positive gradients during the remainder of the year. A typical example is provided in Figure 43. Depicted gradient was observed between Stage I and Stage II during March of 1966. Note the presence of a thin wedge of high velocity water near the bottom, and a thicker surface layer in which sound velocities are slightly lower than at depth. Acoustic beams would be refracted upward in this medium. As shown in Figure 44 (Reference 5), this positive gradient extended at least 20 miles seaward of Stage I. Further downslope, however, a steep negative gradient was encountered within the cold water mass which resides permanently in the Gulf of Mexico's deep central basin.

Sound velocity profiles from within St. Andrew Bay reveal varying degrees of complexity, depending on tide, wind, and season. Typical seasonal traces from a station 1 mile east of NCSC are presented in Figure 45 (Reference 22). These traces show that positive sound velocity gradients are virtually always present at depths greater than 15 feet (4.6 m), but that a negative gradient appears near the surface during spring. The latter is caused by surface heating, while the former is produced by prevailing salinity gradient in bay. Speed of sound is then greater near the surface and bottom than it is at mid-depth, and a tendency exists for acoustic energy to be channeled along this natural duct. During winter, sound velocities as low as 1460 metres per second may be encountered on the surface of the upper bay and adjoining bayous. Depth

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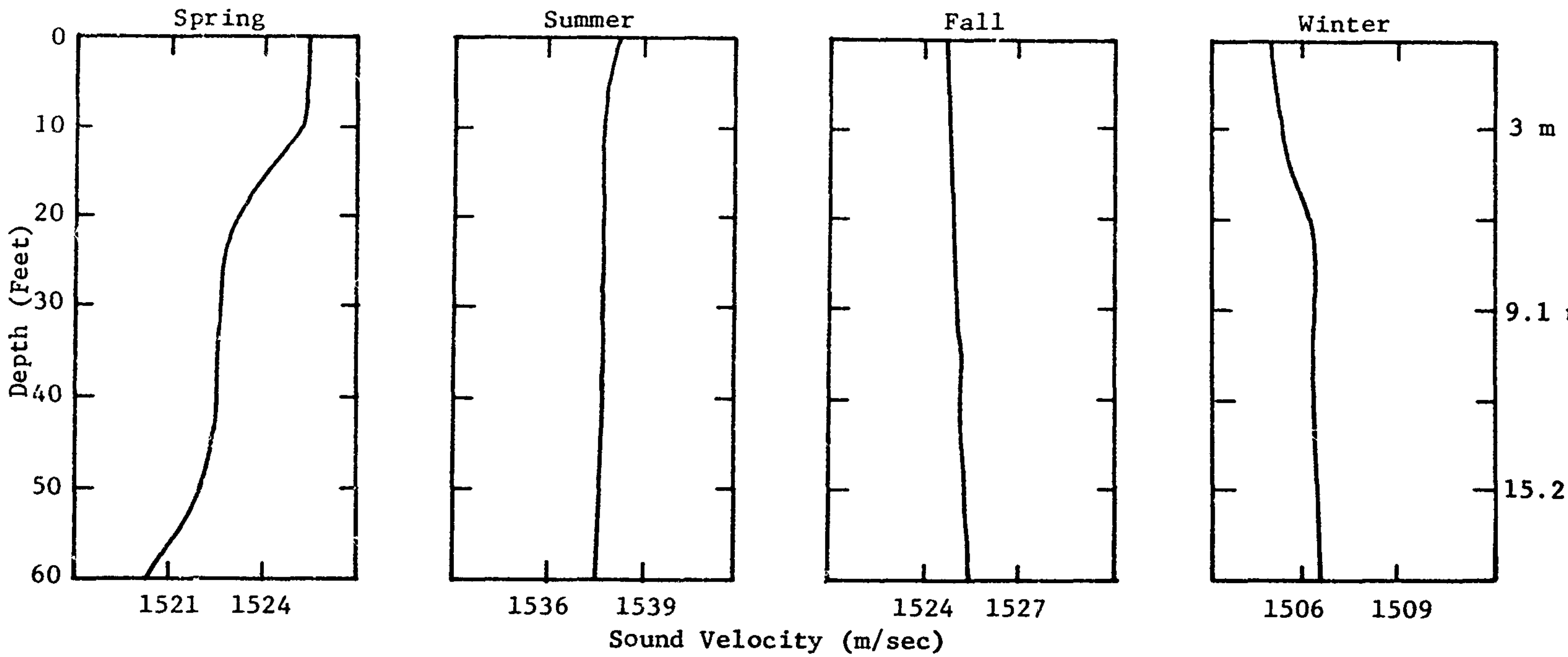


FIGURE 41. TYPICAL SOUND VELOCITY PROFILES FROM STAGE II

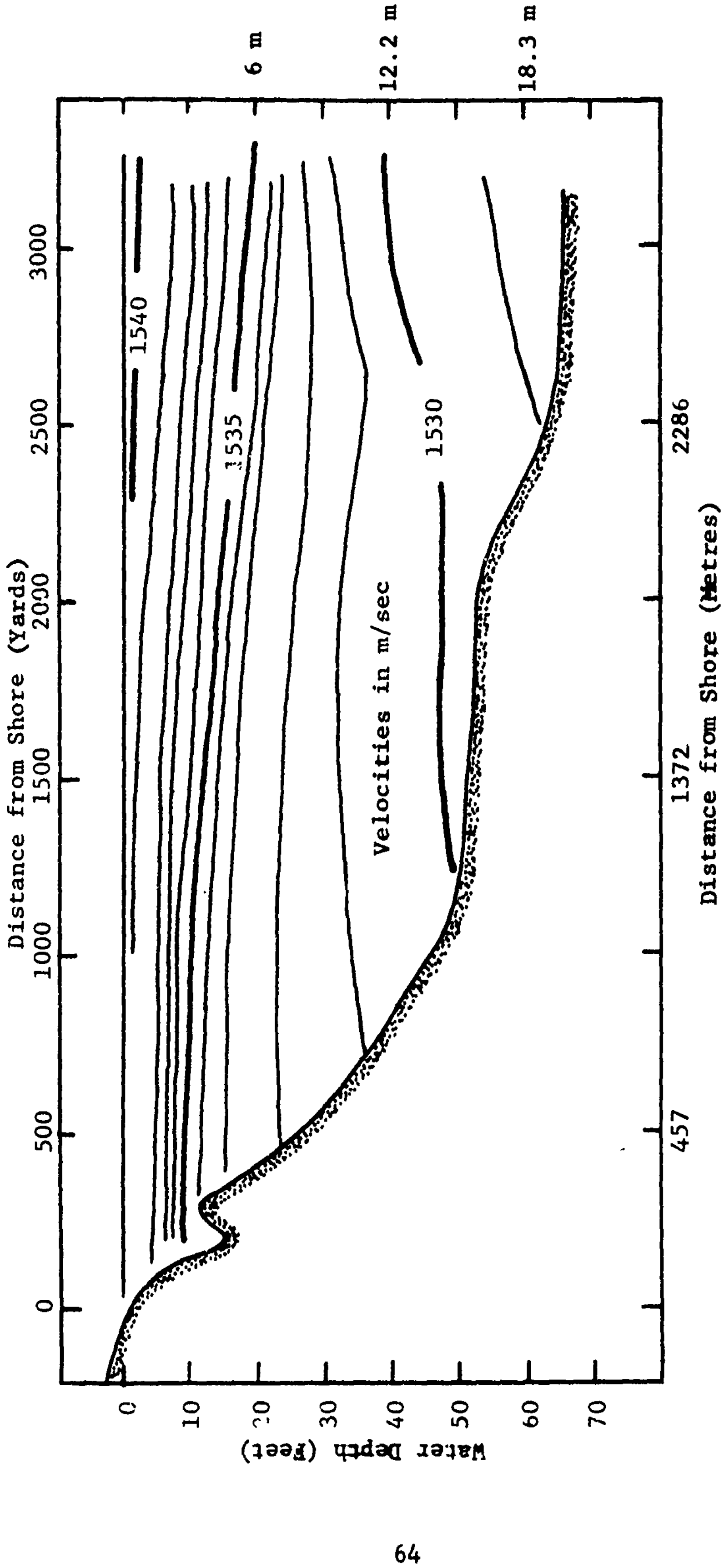


FIGURE 42. SOUND VELOCITY PROFILE IN GULF OF MEXICO NEAR STAGE II

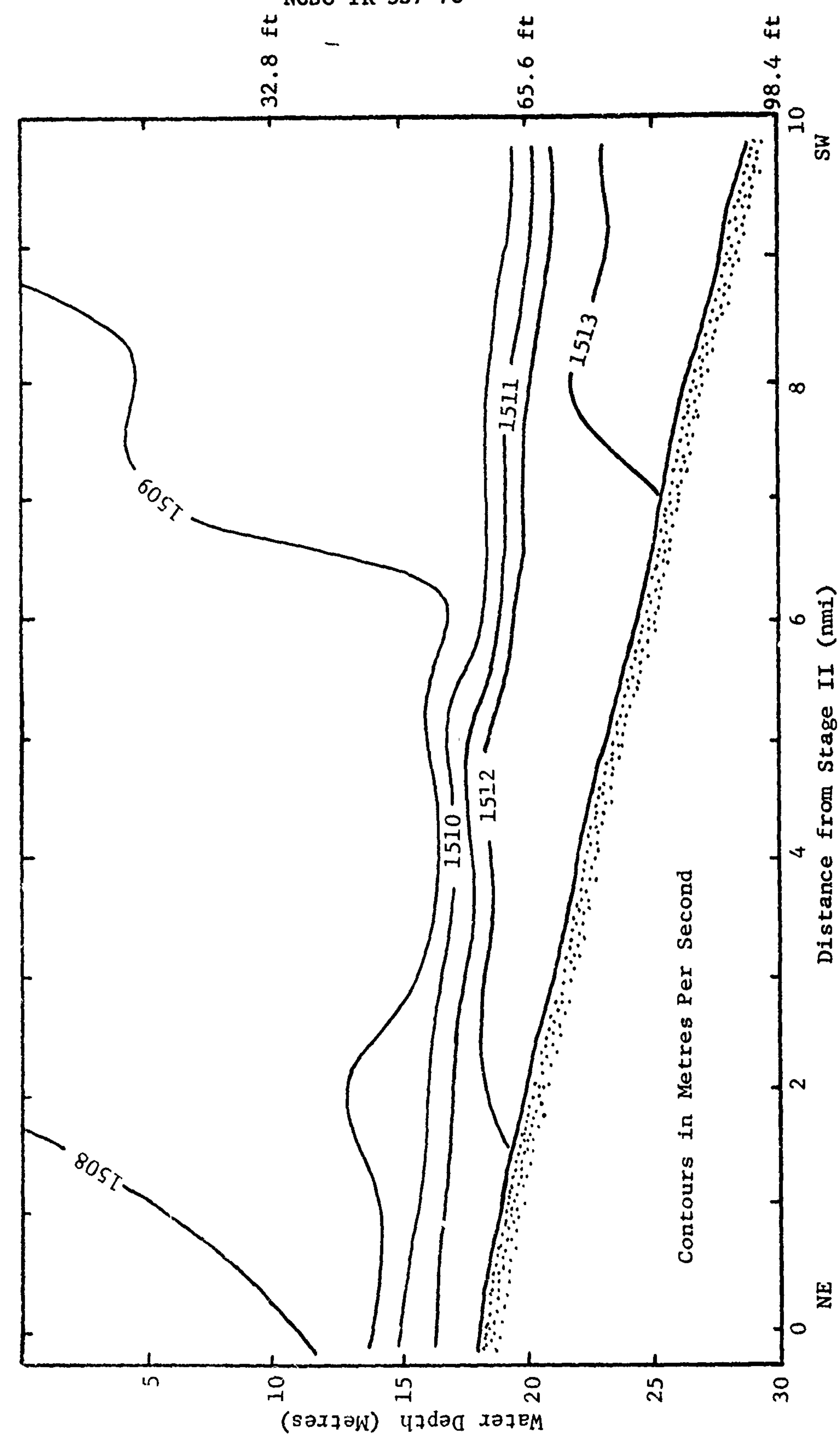


FIGURE 43. SOUND VELOCITY STRUCTURE BETWEEN STAGES I AND II ON 24 MARCH 1976

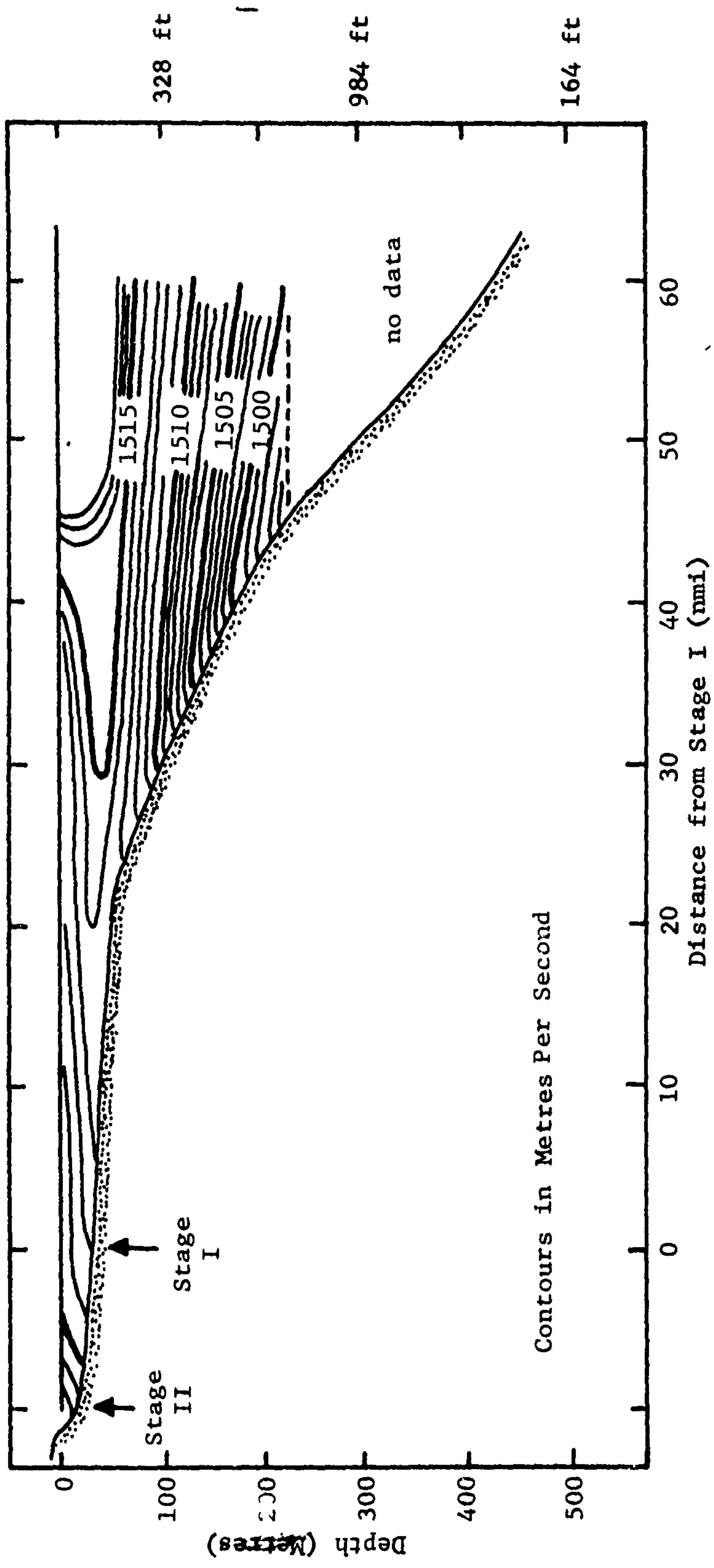


FIGURE 44. SOUND VELOCITY STRUCTURE SEAWARD OF PANAMA CITY ON 28 MARCH 1976

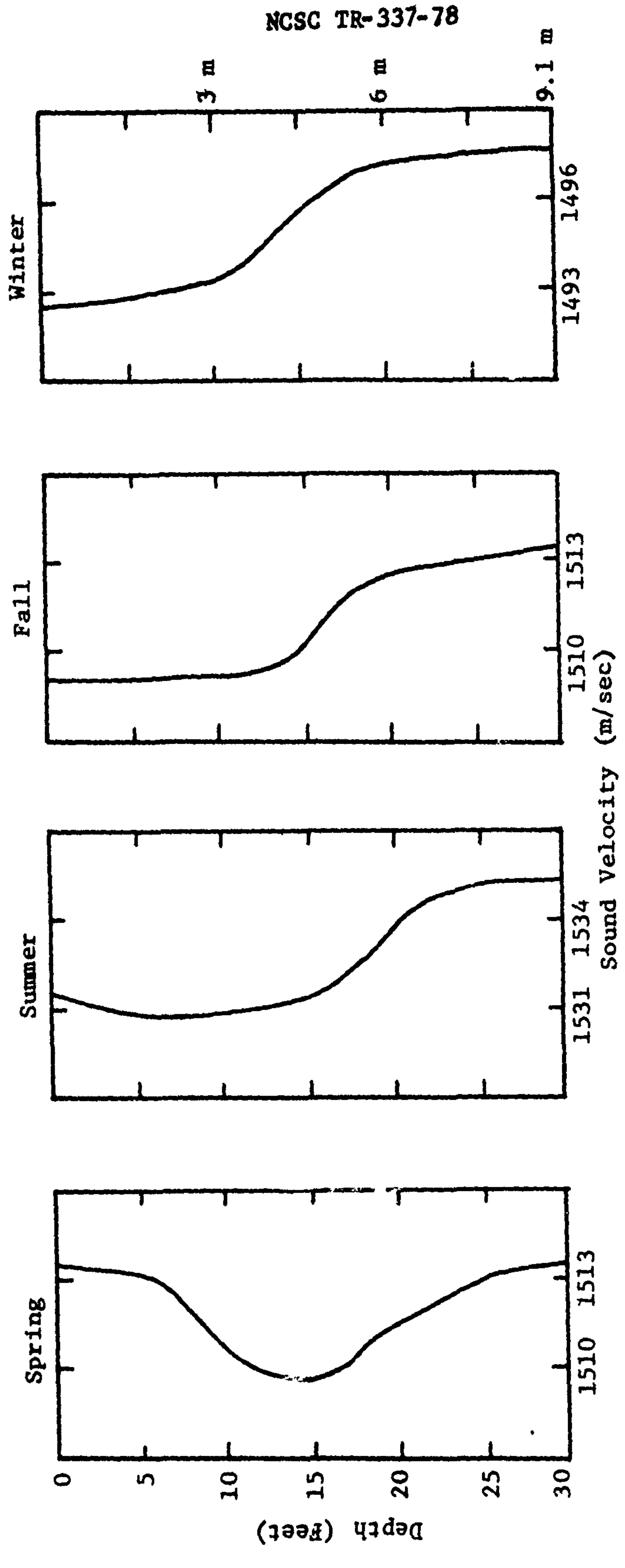


FIGURE 45. TYPICAL SOUND VELOCITY PROFILES FROM ST. ANDREW BAY

of positive sound velocity gradient varies with tide, rising toward the surface during flood cycle and descending toward the bottom during ebb. The amount of rise and fall differs in various parts of the bays, especially near bends. Note the distinctive across-bay tilt of the sound velocity contours in Figure 46. This cross-section is located on the bend in the bay just east of NCSC; as flood tide swerves around this bend along the bottom, it causes sound velocity contours to tilt upward toward west side of channel.

## WATER COLOR AND CLARITY

The local area contains two fundamental types of water, plus an intermediate type which is a variable mixture of the other two. The most important type is found offshore; it is blue in color and exceptionally clear. The second type is found mainly in the bay; it is brown in color and relatively turbid. Intermediate type is found in the vicinity of local gulf beaches; its color and clarity vary considerably. Under normal conditions, it is green in color and relatively clear; but if rainfall is heavy or seas are rough, its color shifts rapidly from green toward brown and its clarity decreases. Conversely, if rainfall is sparse and seas are calm, its color shifts gradually from green toward blue and its clarity increases.

Offshore-type water covers most of the nearby continental shelf, including that portion on which Stage I stands. Divers commonly report underwater visibilities of 20 to 50 metres in the vicinity of this offshore platform. Typical values of the classic volume attenuation coefficient (alpha) range from 0.05 to 0.20 (per metre) (Reference 29). This water occasionally pushes all the way in to local beaches, especially during spring and summer. Brief intervals of poorer visibility may be encountered during winter months when northerly winds push this water further offshore or wave action extends to the bottom and stirs up fine sediments.

Coastal-type water is usually confined within a narrow band adjacent to local beaches. Stage II lies within this band most of the time. Underwater visibilities generally range from 5 to 15 metres in the vicinity of this inshore platform, while values of alpha range from 0.20 to 0.60 per metre. Brief intervals of poorer visibility are encountered whenever wave action becomes heavy or bay effluent is directed seaward, as during passage of "tide line." Surface waves are the primary mixing agent which combine outgoing bay water with nearshore gulf water to produce coastal water mass. Water along local beaches is usually clearer during spring and summer than during fall and winter.

Bay-type water is generated in the shallow upper reaches of the bay system, where fresh water runoff and intruding sea water are mixed by small wind waves, current shears, and associated turbulence. Underwater

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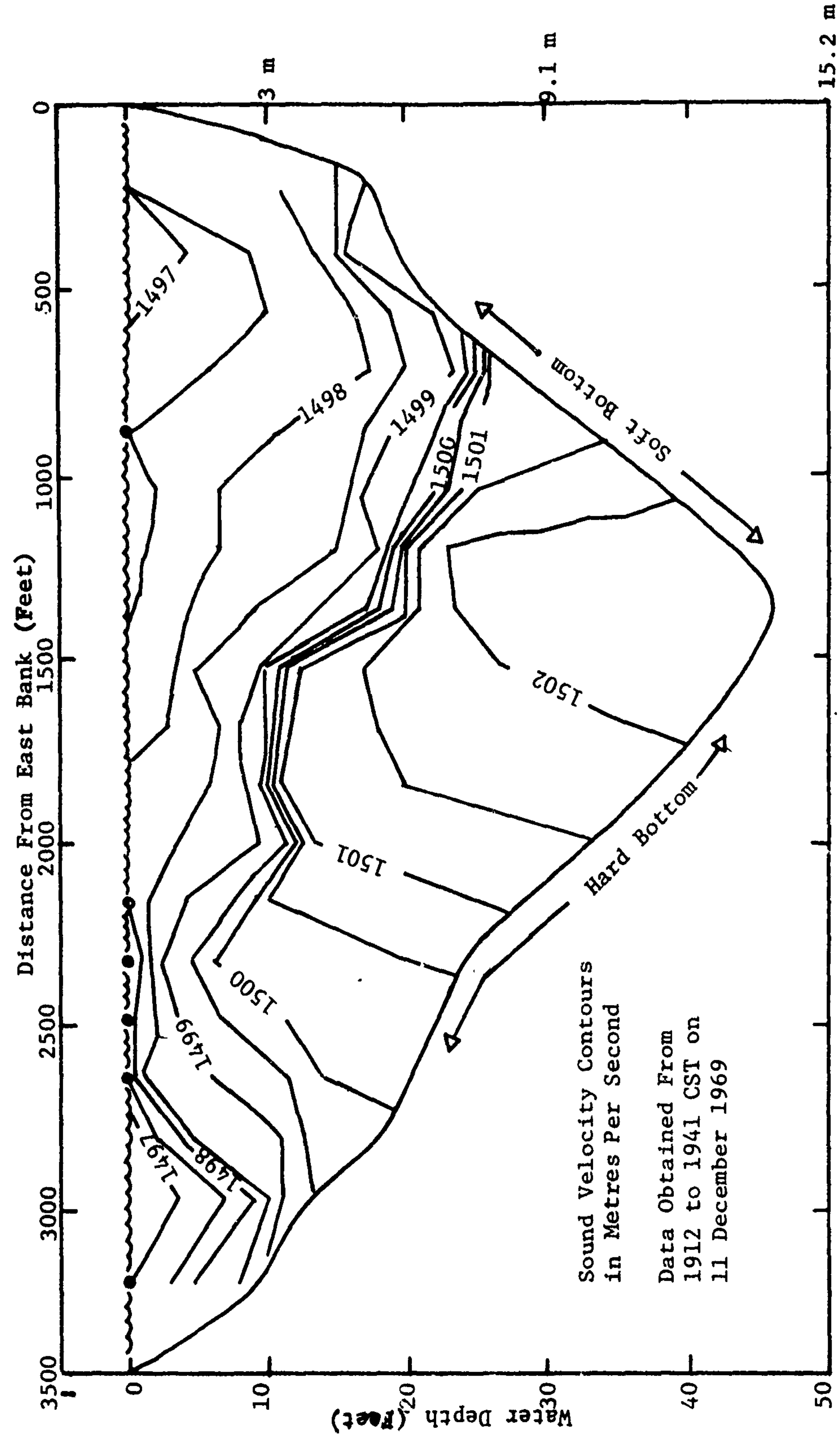


FIGURE 46. SOUND VELOCITY PROFILE AT HATHAWAY BRIDGE DURING FLOODING TIDE

visibilities generally range from 1 to 5 metres in portions of the bay adjacent to NCSC. Typical alpha values range from 1.2 to 2.0 per metre (Reference 30). Visibilities diminish rapidly during periods of increased runoff, and may remain poor (less than 0.5 metres) up to several weeks thereafter. Gradual improvement can be expected during periods of dry weather. Water at subsurface levels in the bay is often clearer than that near the surface, especially near the mouth of bay during incoming tides. Color and clarity of the water within the St. Andrew Bay entrance channel change drastically with each tide cycle, especially during tropic tide periods when currents are strong. Relatively clear coastal water pours into the bay during flood phase, and brownish bay water pours out during ebb phase. Best visibilities are generally encountered near the end of a flood phase and the worst are encountered near the end of an ebb phase.

## BOTTOM CONDITIONS

The local seafloor is characteristically flat and featureless, with sand dominating the scene in the nearby gulf and around the shores of St. Andrew Bay. Thin deposits of mud are found in the protected central basins of the bay system, and along the deeper portions of the continental shelf and slope. A few rock outcrops are present seaward of the 60 foot depth contour in the gulf and at several spots within the man-made segment of St. Andrew Bay entrance channel.

Gulf beaches are composed almost exclusively of fine quartz grains with median diameters of 0.1 and 0.2 millimetres. This fine sand extends out across the shallow barrier bar, and down to depths of 50 to 60 feet (15-18 m), where in many places, it gives way to a coarser brown sand containing numerous shell fragments. Median diameter of this coarser material is 0.3 to 0.5 millimetres. Fines now in residence along local beaches were apparently winnowed out of the deeper sediments by wave action, which elevated them to form the present beach during the last major rise in sea level. This material has been reworked by countless storms since that time. Wave-induced sand ripples, with heights of up to an inch and wave lengths of 3 to 5 inches (7.6 to 12.7 cm) are present much of the time in shallow waters off gulf beaches (Reference 7). Activities of the various members of the sand-dwelling community (such as sand dollars, lug worms, etc.) have been known to flatten these small ripples less than a day after their formation. Large storm waves are needed to generate ripples in the coarser sand found in deeper water. There, right after storms, divers have observed sand ripples with heights of up to 6 inches (15.2 cm) and wave lengths of 3 to 4 feet (0.9 to 1.2 m). It takes bottom dwellers as much as two months to flatten these large ripples.

Medium to coarse grained sand can also be found in the bay's man-made entrance. This channel was originally excavated to a depth of 35

feet (10.7 m) by the Corps of Engineers, but tidal currents have scoured an additional 20 feet (6 m) of sand from the channel floor in some places. Depths of 50 to 55 feet (15.2 to 16.8 m) can now be found at some locations between Shell Island and the mainland. Numerous migratory sand ridges can also be found on the channel floor (Reference 31). Within the land-cut portion of this channel, these ridges vary from 1 to 7 feet (0.3 to 2.1 m) in height. Their crests advance toward the gulf during outgoing tides, and retreat back toward the bay during incoming tides. Ridge fields extend as much as 2 miles (3.2 km) into the bay toward the northeast. Inner ridges average only 1 foot (0.3 m) in height, are composed of fine sand, and migrate in only one direction (toward the northeast) because flood currents are the only effective sand transporting mechanism in this part of the bay (Reference 31).

Narrow beaches of fine sand literally ring the bay, and shallow bars are present at many locations. Oyster reefs can be found on some of the bars within North and East Bays. The remainder of the bay bottom is covered with a thin layer of mud which ranges from less than an inch (2½ cm) to no more than 6 feet (1.8 m) thick. Significant quantities of sand and shell fragments are usually noted within mud samples. Since currents and wave action are generally weak within the bay, one would expect much more mud to have been deposited over the years. But local streams, many of which are spring fed, do not deliver much silt or clay to the bay. hence, even though the St. Andrew Bay system constitutes an ideal settling basin, it has remained essentially unclogged ever since it was formed, and is likely to remain that way for many more years.

Recent depositional history of the nearby continental shelf is quite similar to that of St. Andrew Bay. Waters deeper than 100 feet (30.5 m) are seldom stirred by wave action or currents, and there are no significant local sources of fine sediment. The terrigeneous quartz sands of the inner shelf give way to carbonate and algal sands across the middle shelf, which in turn grades to thin blankets of foraminiferal silt on the outer shelf and slope (Reference 23). Very little deposition has taken place in offshore waters over the years. Limestone outcrops are scattered throughout the area. These reef-like formations (Reference 32) are found in depths of 60 to 230 feet (18.3 to 70 m) of water. Some lie as close as 1 mile (1.6 km) from shore. Most protrude no more than a few feet above the surrounding sediment.

Remnants of an ancient forest have been discovered in 60 feet (18.3 m) of water south of Panama City Beach (Reference 33), and in 20 to 50 feet (6.1 to 15.2 m) of water in the land-cut portion of bay entrance. This latter site was situated beneath the sands comprising the present-day barrier island complex. Wood from these sites ranges from 27,000 to 36,500 years old, and was probably part of a large forest which covered

this area during a period of lower sea level. This forest extended many miles south of our present shoreline. Most of the wood has been identified as pine, but small amounts of hardwood (such as oak, beech, hickory, and elm) have also been found, suggesting vegetation was much like that which presently covers the land 20 to 30 miles north of Panama City. Local beaches, barrier bars, and islands are thus comparatively recent geological features, as is the St. Andrew Bay system.

The entire region is one of the most tectonically stable areas in the world (Reference 23). It has been free of earthquakes for at least as long as records have been kept. Local strata have undergone very little warping, and geologists have been unable to find any significant fault zones. Additionally, local rivers are comparatively small, and are generally flood-free. Even the local beaches are relatively stable, with erosion being a problem only in areas where man-made structures have been placed too close to the water, and have altered normal littoral processes. Serious erosion occurs only during major hurricanes.

Several major oil companies have drilled exploratory wells in a promising area 20 to 30 miles (32 to 48 km) southwest of Panama City. Seismic studies had suggested the presence of one or more salt domes in the area, but no significant quantities of hydrocarbon have been found to date.

## BIOLOGICAL CONDITIONS

A brief description of select members of the marine biological community near Panama City deserves mention not only because the organisms are a part of the local environment, but also because they affect (or are affected by) the ocean researcher and his equipment. Although the effects of wind and waves are often more dramatically detrimental in many situations the more subtle presence of marine organisms, in particular fouling organisms, are of equal concern. The marine designer should at least be aware of some of the detrimental effects their presence can have on his efforts.

The hydrography of the area off Panama City approaches a normal marine environment in its temperature, salinity, and transparency variations, thus exhibiting a typical variety of gulf coast marine life. The submerged bottom of the region consists of well-sorted quartz sand and although this benthic zone is less than prolific, the overlying water is teeming with life (Reference 34). Barracuda, kingfish, bonita, sharks, billfish, snapper, grouper, rays, a thriving commercial fishing fleet, and even an occasional flagellate ("red tide") bloom are all present; but of primary concern to the marine designer are potential equipment restrictions and malfunctions caused by biofouling.

BIOFOULING

Marine fouling (biofouling) is generally considered to be a biological problem that results from the settlement and growth of animals and plants (including bacteria) on the surface of and within objects immersed in the sea by man. Two widely known harmful effects are reduction of the efficiency of ship propulsion and destruction of wharf pilings, but fouling is also a severe problem related to underwater cables, navigational buoys, underwater sound equipment, and various other kinds of oceanographic and military sensing devices.

Considerable variations have been observed in the local biofouling, not only in type of organisms, but also their size and quantity as functions of depth, season, and other factors. Several notable papers have been published. Among these are the works of Pequegnat, Gaille, and Pequegnat (Reference 35), Gaul and Vick (Reference 36), Hulings (Reference 37), Wells (Reference 38), and Braswell (Reference 39). Most of the following data and conclusions are taken from References 34 and 35.

The tendency for biological organisms to settle is influenced by the surface contour, texture and composition, and color of the substratum, as well as by conditions of ambient light, water currents, stage of the tide, the presence of other sessile organisms, depth, and certain physical parameters. Since research material describing each of these effects is available, the following will concentrate on a brief description of the types of organisms prevalent in this area and their variations with season, and to a lesser extent from year to year.

In the Pequegnat study (References 34 and 35) fouling arrays were placed at different depths at Stages I and II, and at a site 25 miles (40.2 km) offshore in the gulf. The artificial substrata, i.e., the fouling arrays, were plastic peanut floats, which were red, smooth, and oval, with a total surface area of 600 $cm^2$.

Seventy-one species of animals and plants were identified on the fouling arrays at Stage II (this number was similar to that found at the other two offshore sites). The more abundant forms included barnacles, hydroids, gammarid amphipods, and pelecypods; among the less abundant organisms are polychaetes, gastropods, anemones, and ectoprocts.

Three species of acorn barnacles (Balanus venustus, B. improvius, B. eburneus), those most likely to be identified by biologists and laymen, occurred regularly at the Stage II fouling arrays. B. venustus greatly outnumbered the other two species. Table 1 lists the total numbers of this barnacle species for two different times of exposure at various depths.

TABLE 1

TOTAL NUMBERS OF B. VENUSTUS FOUND ON
8-WEEK AND 12-WEEK FLOATS
(Pequegnat, et al, 1967)

| Depth (m) | B. venustus |
|---|---|
| **8 weeks** | |
| 4 | 3827 |
| 10 | 3042 |
| 17 | 13,614 |
| **12 weeks** | |
| 4 | 1444 |
| 10 | 2501 |
| 17 | 8272 |

The table shows an increase in B. venustus numbers with depth as well as a relative decrease between the 8 and 12 week exposure period. The decrease in numbers was probably due to overcrowding as both numbers and barnacle size increased. Competition from other late arrival species may also have influenced the decrease in total numbers. The number's increase with depth was consistent with data gathered at other Pequegnat study sites.

During Pequegnat's 2-year study period barnacles exhibited five peaks of attachment (Figure 47), which occurred in spring and winter of each year at each of the test depths of 4, 10, and 17 metres. At a depth of 10 metres spring highs produced numbers of barnacles surpassing those at 4 metres. The lows at 10 metres also corresponded to those at 4 metres, but were less pronounced. The lows at 17 metres, much less extreme than those at 4 and 10 metres, coincided with low times at the latter two depths. The number of barnacles at 17 metres exceeded or equaled the number at 4 and 10 metres during most of the entire 2-year period. Data shown in Figure 47 also point out the extreme yearly variability in barnacle numbers particularly at the shallower depths. As in any biological community, the yearly barnacle population is responsive to a great many environmental factors.

After the cyprid larvae settle on a substrate and transform into sessile form, barnacles exhibit rapid growth. The following were the size ranges of B. venustus at Stage II for the periods shown:

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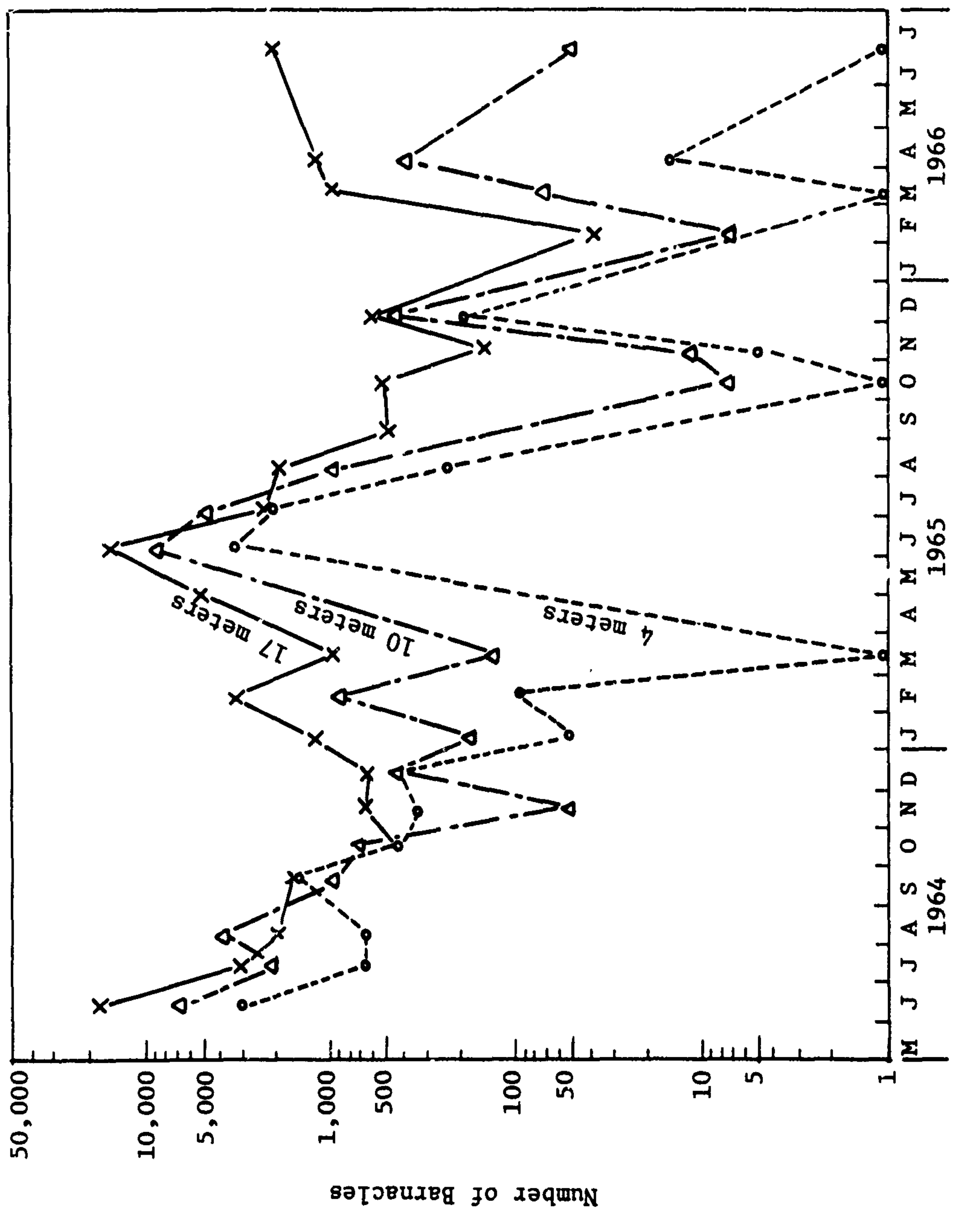


FIGURE 47. BARNACLE COUNT

| Duration of Exposure (weeks) | Range of Size (mm) |
|---|---|
| 2 | 1-7 |
| 4 | 1-9 |
| 6 | 1-11 |
| 8 | 1-12 |
| 12 | 1-13 |

The largest acorn barnacle encountered on 12-week floats was 18 mm. The maximum size of barnacles was not influenced notably by depth but was influenced primarily by the time of cyprid settlement and length of exposure. Attachment of larvae in the northeastern gulf was continuous throughout the year with the exception of mid-March through early April when water temperature was below 16°C.

Five species of gammarid amphipods were identified on the Stage II floats. Although these small crustaceans are not commonly classified as biofoulers their presence may interfere with certain equipment operations. Their numbers usually decreased rapidly with increase in depth. Although gammarids were abundant throughout the year, they were extremely abundant during March, April, and May. On two separate occasions over 20,000 individuals (33 per $cm^2$ of float surface) were present on 4-meter floats. Gammarids appear as matted and tangled tubes in layers 5 to 10 mm thick, sometimes projecting as irregular mounds to a height of 25 mm or more above the substrate.

Twenty-three species of hydroids were found at Stage II, of which seven appeared in abundance. Maximum lengths varied from 15 to 100 mm. Data taken at Stage II indicate equal occurrence at the three depths of 4, 10, and 17 metres, and were most abundant in May through December with a slight peak in September and October.

The stages of development of a marine fouling community deserve mention. Some predictable events occur in this development of fouling assemblages with the passage of time. Among the more pronounced of these are: (1) the early appearance and rapid development of pioneer settlers, (2) a rapid, then more gradual increase in the species diversity, (3) an early increase in size and numbers of individuals of all species, (4) the decrease in population of some species and the complete elimination of others, and (5) the predominance of a few species with their development attracting yet other species that are late settlers. At each step the substrate surface, which has then become a biological coating, is gradually conditioned for the late comers.

The pioneers are invariably bacteria, diatoms, and blue-green algae, which produce a slimy surface. Barnacles, hydroids, and gammarid

amphipods generally appear during the first week of exposure. These early arrival species are primarily suspension feeders, removing particulate matter from the circulating water. Still later come carnivores, scavengers, omnivores, herbivores, and deposit feeders. Thus the assemblage of animals acquires the characteristics of a community with a full representation of feeding types.

Biofouling data from Stage I and the 25-mile site are similar to those found at Stage II. The same species are common to all three sites although a slightly higher number (100) have been identified by Pequegnat at the 25-mile location.* Figure 48 shows a seasonal variation of barnacle numbers at the 25-mile site similar to that at Stage II. Fouling numbers appear in general to increase with depth to below the 45 metre level. Note, too, the consistently low numbers during the March period.

The discussion thus far has dealt exclusively with offshore; i.e., Gulf of Mexico, waters. Of equal interest is the environment to be encountered within the St. Andrew Bay system. Although these waters are directly connected to the gulf, they constitute an estuarine environment with somewhat different salinity, temperature, and tidal variations than those found offshore. As a result, the fouling species and their distribution are somewhat different.

The most notable difference between bay and offshore biofouling is the dramatic decrease in organism settlement and growth found in the bay during the winter months (i.e., November - March). Although quantitative data supporting this observation are not presently available, NCSC has during 1976-1977 formally observed fouling growth on metal and plastic plates exposed in the bay which support this contention. The

* Several factors determine the types of foulers found at a particular location. In addition to general geographic considerations, these are depth, distance from shore, and presence or absence of suitable currents.

The speed of the current is an important consideration. If it is too fast (2 knots or more) larvae may not be able to attach. (Also, as in the case of the moored floats at Stage II, more forms often settle and grow faster on the downstream than the upstream side). On the other hand, a certain speed may be an advantage to a particular species in view of the fact that its larval-life span is finite. These organisms must reach a suitable substrate during this period.

(Text Continued on Page 79)

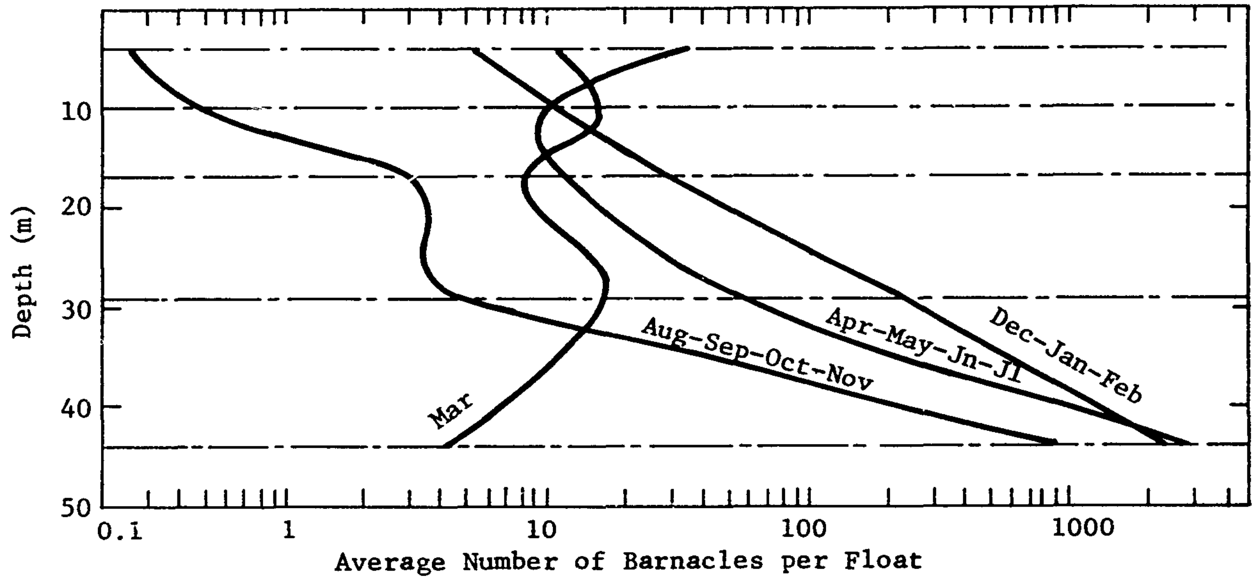


FIGURE 48. YEARLY BARNACLE VARIATIONS AT 25-MILE TEST SITE

entire fouling community appears to be affected during these months of limited growth with the possible exception of bacteria whose slime film is still evident on exposed substrata (although to a lesser degree than during a comparable summer period), and some algae which also attach. Barnacles and other fouling organisms have been observed to attach during the winter but their numbers are relatively insignificant.

During the summer biofouling season, which for the bay begins as water temperatures approach 20°C, a complete biofouling community is evident. The organisms of particular concern are the barnacles, namely the species B. eburneus which is dominent in the upper layers of bay waters, annelids (a calcarious tube worm), bryzoans, and in the final stages of community development, Tunicates or Acidians. Tunicates will eventually dominate the substrate forming a consistant layer 30-40 mm thick.

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